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A Review of Literature
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of Research Needs

October 1964

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U.S. DEPARTMENT
OF HEALTH, EDUCATION,
AND WELFARE
Public Health Service

INFLUENCE OF IMPOUNDMENTS ON WATER QUALITY

A Review of Literature and Statement of Research Needs OCTOBER 1964

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U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Division of Water Supply and Pollution Control

Cincinnati, Ohio

October 1964
Revised — January 1966

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Public Health Service Publication No. 999-WP-18

FOREWORD

The enactment on July 20, 1961, of Public Law 87-88, an amendment to the Federal Water Pollution Control Act (P.L. 660), caused the Federal construction agencies, e.g., the Corps of Engineers and the Bureau of Reclamation, to begin giving consideration to the inclusion of storage for regulation of streamflow for the purpose of water quality control in the survey or planning of any impoundment. Since, according to P.L. 87-88, the need for and the value of storage for this purpose shall be determined by these agencies with the advice of the Secretary of the Department of Health, Education, and Welfare, the act instructs the appropriate group in the Department to do whatever basic and applied research is necessary to permit evaluation of the effects on water quality and water uses of regulated streamflow to control water quality. The Engineering Section of the Basic and Applied Sciences Branch of the Division of Water Supply and Pollution Control at the Robert A. Taft Sanitary Engineering Center is the designated group to make these studies.

Research on the influence of impoundments is a portion of a project entitled "The Effects of Streamflow Regulation on Water Quality." Since any streamflow regulation project having the goal of water quality control involves the release of impounded waters at times of deteriorating downstream water quality, the influence of impoundments on water quality must be known if the project is to be successful. A discussion of this phase of streamflow regulation is the major concern of this report.

Two other aspects of streamflow regulation are so closely associated with impoundment behavior that they are also included in this report, although to a lesser extent. One is the influence of impoundment releases on downstream water quality, and the other is the use of the systems analysis approach correlated with economic analysis for the optimization of large water quality control projects.

This report is broad by design, touching on the fields of chemistry, microbiology, algology, physical phenomenon, measurement technology, stream self-purification, economics, and systems analysis, since one of the important purposes of the report is to indicate to readers who are new to the field of impoundment behavior and streamflow regulation the enormous breadth of these fields. The other two purposes are: (1) to discuss each topic in sufficient detail to give the reader insight into the current understanding of that topic and (2) to indicate the major research needs in each problem area and to suggest possible fruitful avenues of study to satisfy these needs.

To achieve these purposes, an intensive review was made of over 600 literature references. The 147 most pertinent were then selected as the basis for this report. Since this report summarizes current

thinking on each topic, the selected references for the most part are current ones. About 80 percent of them were published from 1958 to 1964. A reader wishing to delve further into a given topic will find the bibliographies in the documents referenced most useful in leading him back through the literature.

Since an important objective of this report is to indicate the research needs in various areas, the gaps and insufficiencies in current knowledge are pointed out in each subsection. This was done, not in an effort to cast doubt on the value of the work done by others, but to indicate that in most areas relating to impoundment behavior more work needs to be done before the subject is completely understood. The sections devoted to research needs are often stated in general terms because a need has been recognized, but a specific and detailed plan of attack has not yet been formalized. In this orienting and summarizing report, this approach seems perfectly proper.

In summary, this report attempts to indicate: (1) the broad scope of influences that impoundments have on water quality, (2) the existing information connected with various phases of these influences, and (3) some of the most pressing research needs in this area. This report can serve to guide research, not only within the U. S. Public Health Service, but also in universities, private research organizations, and other governmental agencies.

The authors wish to thank the following persons for their helpful and critical reviews: Mr. Bernard B. Berger, Mr. Frank E. DeMartini, Mr. Frank H. Rainwater, Dr. William M. Ingram, Mr. Kenneth M. Mackenthun, Mr. John E. McLean, Mr. Robert W. Haywood, Jr., and Dr. Richard L. Woodward.

At the time of the original preparation of this review, the authors were assigned to the Engineering Section of the Basic and Applied Sciences Branch of the Division of Water Supply and Pollution Control in the U. S. Public Health Service. The passage of Public Law 89-234, an amendment to Public Law 84-660, on October 2, 1965, reorganized a portion of the U. S. Department of Health, Education, and Welfare and assigned the mission of the Division of Water Supply and Pollution Control to the newly created Federal Water Pollution Control Administration. After January 1, 1966, therefore, the research efforts in the area covered by this report will be carried out by this new agency.

Cincinnati, Ohio
January, 1966

James M. Symons
Samuel R. Weibel
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CONTENTS

Abstract vii
Introduction 1
Behavior of Water in Impoundments 5
Measurement of Water Quality in Impoundments 5
Hand Sampling 5
Existing Information 5
Research Needs 7
Continuous Monitoring 7
Existing Information 7
Research Needs 8
Development of Organisms 9
Eutrophication 9
Existing Information 9
Research Needs 12
Light Penetration and Turbidity Removal 13
Existing Information 13
Research Needs 14
Oxygen Production and Demand 14
Existing Information 14
Research Needs 17
Carbonate Equilibrium 18
Existing Information 18
Research Needs 19
Nutrient Removal 19
Existing Information 19
Research Needs 21
Inorganic Substances 22
Dissolved Oxygen 22
Existing Information 22
Research Needs 23
Nitrogen 23
Existing Information 23
Research Needs 25
Phosphorous 26
Existing Information 26
Research Needs 26
Sulfur 27
Existing Information 27
Research Needs 27
Iron 28
Existing Information 28
Research Needs 29
Manganese 30
Existing Information 30
Research Needs 31
Nutrients 32
Existing Information 32
Research Needs 32

Organic Substances 33
Oxidation and Persistence of Organics 33
Existing Information 33
Research Needs 34
Methane 34
Existing Information 34
Research Needs 35
Color 36
Existing Information 36
Research Needs 37
Physical Factors and Environmental Influences 37
Thermal Stratification 37
Existing Information 37
Research Needs 38
Density Flows 40
Existing Information 40
Research Needs 41
Artificial Destratification of Impoundments 42
Existing Information 42
Research Needs 43
Evaporation Control 44
Existing Information 44
Research Needs 46
Thermal Pollution 46
Existing Information 46
Research Needs 48
Summary of Russian Experiences 48
Influence of Impoundment Releases on Downstream Water Quality 49
Influence on Quality 49
Existing Information 49
Research Needs 50
Turbulent Diffusion and Natural Mixing 51
Existing Information 51
Research Needs 54
Operations Research for Water Quality Management 57
Mathematical Analysis 57
Existing Information 57
Research Needs 58
Economic Analysis 59
Existing Information 59
Cost/Benefit Ratio 59
Recreation 60
Loss Functions 61
Research Needs 61
Current Streamflow Regulation Projects and Future Activities . . 63
Current Projects 63
Future Activities 67
Bibliography 71

ABSTRACT

Since streamflow regulation is currently being considered as a method of water quality control and impoundments will be the source of water for regulated streamflow, the changes in water quality that occur during storage in a given environment must be understood and predictable. Much has been written in the sanitary engineering and limnology literature that bears on the broad problem of determining the influence of impoundments on water quality. This report is a review of that literature. It is impossible to report on all of the literature, but sufficient selected references are reviewed to accomplish three purposes: (1) to indicate to readers who are new to the field of impoundment behavior the enormous breadth of the field, (2) to discuss each topic in sufficient detail to give the reader insight into the current understanding of that topic, and (3) to indicate the major research needs in each area and to suggest possible fruitful avenues of study to satisfy these needs. In addition to the major section on impoundment behavior, this report contains sections on the influence of impoundment releases on downstream water quality and operations research for water quality management.

The Engineering Section of the Basic and Applied Sciences Branch of the Division of Water Supply and Pollution Control at the Robert A. Taft Sanitary Engineering Center is the group designated to conduct research on this subject.

INFLUENCE OF IMPOUNDMENTS ON WATER QUALITY

A Review of Literature and Statement of Research Needs

INTRODUCTION

The initiation of research by the U. S. Department of Health, Education, and Welfare on the influence of impoundments on water quality was stimulated by Section 4(d)(1) of Public Law 660 as amended by P.L. 87-88, enacted July 20, 1961, which states in part:

> "Section 4(d)(1) In carrying out the provisions of this section the Secretary shall develop and demonstrate under varied conditions (including conducting such basic and applied research, studies, and experiments as may be necessary):
>
> (C) Methods and procedures for evaluating the effects on water quality and water uses of augmented streamflows to control water pollution not susceptible to other means of abatement."

and by Section 2(B) (1 and 2), which states:

> "(b)(1) In the survey or planning of any reservoir by the Corps of Engineers, Bureau of Reclamation, or other Federal agency, consideration shall be given to inclusion of storage for regulation of streamflow for the purpose of water quality control, except that any such storage and water releases shall not be provided as a substitute for adequate treatment or other methods of controlling waste at the source.
>
> (2) The need for and the value of storage for this purpose shall be determined by these agencies, with the advice of the Secretary, and his views on these matters shall be set forth in any report or presentation to the Congress proposing authorization or construction of any reservoir including such storage."

This very large research mandate, under the general project title "The Effects of Streamflow Regulation on Water Quality," has been initially divided into five parts for study:

1. Characterization and treatment methods for stormwater runoff from urban areas.
2. Characterization and treatment methods for stormwater runoff from rural areas.
3. Investigation and reevaluation of stream pollution criteria.
4. Determination and prediction of the behavior of water quality in flowing streams.
5. Determination and prediction of the behavior of water quality during impoundment.

The discharge of untreated or partially treated stormwater runoff from urban and rural areas is important since it represents one source of "water pollution not suceptible to other means of abatement," to quote amended P.L. 660. Studies on urban runoff have been summarized by Weibel, Anderson, and Woodward,[1] and reviews similar to this one are being prepared on urban and rural runoff. Stream pollution criteria and the behavior of water quality in flowing streams are important since stream pollution of all forms must be recognizable and the influence of dilution water on stream behavior must be predictable. Finally, the changes that occur in water quality during storage in a given environment must be understood and predictable since impounded water is the source of water for regulating streamflow. If a streamflow regulation project is to be successful, the capability to forecast the quality of the water available for dilution must be developed.

The literature on the behavior of water quality during impoundment was extensively reviewed for this report. This review was then summarized so that the current state of information relating to various phases of the problem could be reported and the future research needs delineated. Although the major emphasis in this report is on the problem of the determination and prediction of the behavior of water quality during impoundment, the closely related problem of the influence of impoundment releases on downstream water quality and the use of systems analysis methods coupled with economic analyses for streamflow regulation project design is also discussed. The legal aspects of streamflow regulation for water quality improvement, such as the problem of water rights, are not, however, covered.

In reviewing the literature on the topics of stream and impoundment behavior, one is immediately struck by the vastness of the writings on these subjects. This is reasonable, however, since these two topics encompass almost the entire sciences of sanitary engineering and limnology, both of which are broad fields of study. Most articles are a detailed description of some particular research that adds new knowledge in a specific area of interest, but some works, such as "Water Pollution — Economic Aspects and Research Needs," by Allen V. Kneese,[2] discuss the overall problem, as do the reports to the Select Committee on National Water Resources, United States Senate.[3] An example of research covering the broad problem is the

U.S. Public Health Service Research and Training Grants Branch's 6 years of sponsored research (Grant number WP-00153) at the Johns Hopkins University on the subject "Low-Flow Augmentation for Stream-Pollution Abatement."[4]

With so much literature on the subject, one might wonder whether problems could still exist; but many do. In spite of all of this research, sufficient information is not available to permit the choice of one impoundment site from among several in a given geographical area that will have the minimum adverse effect on the quality of the water and that will, therefore, provide the best quality water. Further, if an impoundment site is fixed, sufficient information is not available to permit prediction of how the quality of the incoming water will be changed as it stands in this impoundment. Finally, because of this lack of understanding, firm recommendations cannot be made relating to outlet structure design, impoundment operating practices, or in-impoundment control since the influence of changes in these items on discharged water quality is not known.

Why, with so much research in the appropriate general area, does uncertainty still exist in the ability to predict the influence of impoundments on water quality? There are at least three reasons. First, much of the data, though generally applicable to the understanding of impoundment behavior, has not been taken with impoundment behavior specifically in the researcher's mind. For example, extensive research by limnologists and aquatic biologists has related the growth of algae to light intensity and penetration. Little attention has, however, been paid to the increased light penetration that is caused by impounding a turbid river water and to the potential organism growth problem that this clarification may pose.

Second, many of the investigations have not been fundamental enough to allow the observed phenomena to be projected into a new set of environmental conditions. For example, for years thermal stratification has been noted in impoundments, yet the necessary set of environmental circumstances that enhance the possibility of thermal stratification has never been completely delineated.

Third, the environmental conditions in an impoundment differ from those in a flowing stream in many ways, e.g., changes in water depth, increased detention time, and possibility of thermal stratification. Each influences the normal biological, physical, and chemical processes that cause changes in water quality.

Many of these processes have been studied under flowing stream conditions, but have not been investigated in impoundment environments where the additional detention time allows natural processes to proceed far beyond the extent possible in a flowing stream. In addition, if thermal stratification exists in an impoundment, the fact that the bottom portion of the water is trapped and does not contact the atmosphere or aerated water has a marked effect on the natural processes that occur in the water.

In impoundment environments, therefore, it is necessary to: (1) investigate new relationships thoroughly, (2) reinvestigate known re-

lationships, (3) relate previously observed results to the environmental factor or factors that caused them so that in a different environment different results can be predicted. Until these three important general research needs in the area of impoundment behavior are met, streamflow regulation projects for quality control will not be found on a firm scientific basis. Despite the predictions of impoundment and stream behavior currently being made, there is need for greater knowledge.

The report is divided into three major sections: (1) the behavior of water in impoundments, (2) the influence of impoundment releases on downstream water quality, and (3) operations research for water quality management. Each major heading is subdivided for clarity; each subsection contains sections on "Existing Information" and "Research Needs." A summary of current streamflow regulation projects and future research activities is also included.

BEHAVIOR OF WATER IN IMPOUNDMENTS

Measurement of Water Quality in Impoundments

HAND SAMPLING

Existing Information

The effect of impoundments on water quality and the measurement of water quality in impoundments have been under investigation for many years. The earliest reference found is an article published in 1890 by Stearn,[5] "Effect of Storage on the Quality of Water." Since that time, and continuing to the present with projects such as the study of the water quality in Lake Michigan under the auspices of the Great Lakes - Illinois River Basin project, data have been taken, and articles written concerning the quality of water in impoundments.

This review developed 80 references to water quality studies in specific impoundment locations, and the list is not exhaustive. In spite of this wealth of information, the generalized behavior of water quality in impoundments is not completely understood, mainly because of the method by which the data in these individual studies were taken. Often, these data represent an isolated set or a series of sets of hand samples that were analyzed for the common chemical and biological water quality characteristics. In general, no attempt was made to: (1) measure the changes that occurred in water quality with time or (2) relate the magnitude of any given change to the environmental condition influencing it. While these studies served the purpose for which they were intended, in the longer view they consisted more of "data taking" than of research investigations. This is often true of field investigations. Two reports that attempt to avoid the first difficulty mentioned will be noted in detail later.

In addition to numerous reports on the measurement of the quality of lakes and impoundments, several articles sought to discuss in qualitative terms the influence of impoundments on water quality. One article by Churchill,[6] "Effects of Storage Impoundments on Water Quality," covers most of the generalized effects of impoundments on water quality. The data taken by the Tennessee Valley Authority during 20 years of operation are discussed in detail with emphasis on the following:

1. Development of thermal stratification and its effects.
2. Reduction in turbidity due to the storage capacity of reservoirs.
3. Reduction in color concentration due either to biological activity, sunlight, or the equalizing action of the impoundment.

4. Possible production of H_2S odor or algal odor.
5. Reduction in coliform organisms.
6. Effect of impoundments on BOD and dissolved oxygen in the water.
7. Buildup of free carbon dioxide in the bottom waters of stratified reservoirs.
8. Possible nitrification and denitrification in impoundments.
9. Possible dissolution of iron and manganese in bottom waters.
10. General equalization or smoothing effects of a storage impoundment on mineral quality.

The article also discusses reaeration of deoxygenated water below dams. In spite of the usefulness and thoroughness of this article, the author's remark that, "The facts obtained and the general principles deduced therefrom should be helpful in forecasting the changes in water quality that are likely to occur in any proposed reservoir," seems premature.

An article by Love,[7] "Relationship of Impoundments to Water Quality," discusses similar subjects with the addition of density flows in impoundments, heat dissipation in impoundments, and behavior of radioactivity in impoundments. His conclusion differs somewhat, however, from Churchill's in that he states:

> "Many studies of stream impoundments have been made, and much valuable information has been obtained. Unfortunately, most of the studies have been more qualitative than quantitative. Even when water characteristics have been reported quantitatively, overall evaluations of water storage projects and their relation to multipurpose interests have been largely qualitative. There is an increasing need for more thorough studies of stream impoundments in terms of parameters usually passed over lightly or completely ignored."

At least two reports have attempted to measure water quality as it changes with time. One, "Mainstem Reservoir Effects on Water Quality in the Central Missouri River," by Neel, Nicholson, and Hirsch,[8] measures the effect of six mainstem reservoirs on the quality in the Missouri River over the period 1952 to 1957. Although all the environmental conditions that cause changes in water quality are not given, several explanations for the observed effects are given. These discussions help make the data in this report useful for understanding the generalized behavior of impoundments. The noted effects cannot be applied indiscriminately, however, since these reservoirs do not thermally stratify and exhibit slug flow with the minimum of longitudinal mixing, which may be the case in most run-of-river impoundments. In spite of these limitations, this study is valuable.

A similar study was made from March 1945 to March 1946 by the Tennessee Valley Authority. During this time 89 samples

taken above and below Cherokee Reservoir were analyzed for common water quality characteristics. These included: temperature, dissolved oxygen, BOD, color, pH, alkalinity, CO_2, all four nitrogen forms, turbidity, solids, phosphorus, manganese, and chlorides. In addition, coliform organism densities were determined. Although no environmental conditions were noted, these data give an excellent picture of the change in water quality as water passes through a stratified impoundment.

Because of the stratification and resulting density flows, the holdup time for any given influent water varied throughout the year. In the fall of the year the cool influent water flowed directly along the bottom under the warmer reservoir water and out the penstocks in as little as 2-1/2 weeks. During the spring and summer the detention time was found to be as long as 25 weeks because the warm influent water spread across the surface of the impoundment and was slowly drawn down to the outlet level to operate the power turbines. The warm influent never appeared as a distinct volume of water. In view of the different behavior of the warm and cold influents, any comparison of influent and effluent data from this study should be considered with caution. The Cherokee Reservoir study is, however, the most complete evaluation of the changes in water quality in a stratified impoundment found in the literature search. The data have not been published, however, and were obtained through a private communication from Milo Churchill, Chief of the Stream Sanitation Staff of the TVA.

Research Needs

Field research investigations need to be made, and the data taken should be correlated with the environment. This is important since the great mass of data in the literature does not permit generalization because of variations in impoundment geometry, soil conditions, environment conditions, and so forth.

Environmental factors that should be reported are: character of soils in bottom and bank storage areas; length, width, and depth ratios of the reservoir; reservoir orientation; wind direction and velocities; solar radiation intensity; and light penetration. These environmental data, correlated with adequate numbers of samples taken over an extended period of time, should allow a relationship to be drawn between environmental conditions and the changes in water quality. Care must be taken in the definition of significant factors and the design of the experiment since a mass of data is of limited use if it cannot be interpreted in such a manner as to permit the emergence of a general law, assuming one exists.

CONTINUOUS MONITORING

Existing Information

The development of instrumentation for continuous monitoring of water quality is just beginning. Several continuously recording monitors that make a permanent record of such characteristics as

dissolved-oxygen concentration, pH, conductivity, temperature, turbidity, solar radiation intensity, and air temperature are currently commercially available. Water levels and other weather information can also be recorded, if required. An article in *Chemical and Engineering News*, "Monitor System Continuously Records River Water Quality,"[9] describes a continuous monitoring system operating on the Delaware and Schuylkill Rivers. Ragone and Peters[10] in a paper entitled "Water Quality Monitoring for Water Quality Control," describe a continuous monitoring system that the Virginia Electric and Power Company has on the Roanoke River in North Carolina. Continuous monitoring is important to the power company since its Federal license contains a specification for minimum allowable dissolved-oxygen concentration downstream from the dam. They must, therefore, continuously monitor the dissolved-oxygen concentration downstream from their power dams to have continuous proof of compliance with the provisions of the Federal license. Cleary[11] in his article "An Electronic Monitor System for River-Quality Surveillance and Research," describes the continuous monitor developed for ORSANCO.

Research Needs

The research needs in this area fall into four categories: (1) testing and improvement of available continuous monitors, (2) development of methods of continuously monitoring other water quality characteristics; (3) adaptation of existing monitors designed for use in flowing water to impoundment studies, and (4) collection of significant amounts of continuous quality data in existing impoundments. The Basic Data Branch of the U.S. Public Health Service has done much in developing and evaluating monitors. Their current results are summarized in "How Automation Plays a Part in Water-Quality Surveillance" by McCallum and Stierli[12] and "Instrumentation in Water Quality" by Mentink.[13]

Although field data must be carefully taken to avoid some of the criticisms mentioned above, there can be no doubt that extensive field data must be taken to confirm the applicability of laboratory experiments to prototype conditions. These data can probably be best taken by continuous robot monitors, which reduce the manpower necessary to take the data and provide a continuous record of water quality rather than an intermittent record resulting from periodic grab samples.

Data should also be taken throughout the depth of an impoundment. Immersing the sensing elements to the appropriate depth seems a better scheme than pumping the sample to the surface for monitoring since the latter procedure may cause changes in the quality characteristics to be measured. The development of completely submersible sensing units is a logical alternative and presents another research need.

GPO 823-506-2

EUTROPHICATION

Existing Information

Limnologists, aquatic biologists, and sanitary engineers have shown increasing concern in recent years about the continual tendency toward eutrophication of lakes and impoundments. Some recent studies and reports on Lake Geneva,[14] Lake Constance,[15] and Lake Tahoe[16] are examples of publications expressing concern about the condition of large lakes. The one major concern about these lakes is the increasing potential for the development of nuisance organisms, mainly algae, because of the addition of domestic wastes. These wastes tend to supply the nutrients for algae growth. Their increasing concentration presents, therefore, a potential hazard with respect to the degradation of the lake through the excessive growth of nuisance algae.

Much research effort has been directed by various investigators toward determining the nutrient requirements of various species of algae. Much of this research has tried to determine the minimum nitrogen and phosphorus concentrations that would permit the growth of algae. Widely quoted figures are given by Sawyer[17] in "Fertilization of Lakes by Agricultural and Urban Drainage". A portion of this important reference is quoted below.

> "All the evidence obtained in the Madison survey lends support to the belief that phosphorus is a key element in determining the biological activity in a body of water. The data regarding critical levels of organic phosphorus are not too well correlated but, in the main, show that most of the lakes producing nuisance blooms have average concentrations in excess of 0.10 ppm (100 μg/l). The data concerning critical levels of inorganic phosphorus, however, are much more decisive and indicate that nuisance conditions can be expected when the concentration of inorganic phosphorus exceeds or equals 0.01 ppm (10 μg/l).
>
> The importance of nitrogen in supporting algal blooms cannot be denied. A critical level of 0.30 ppm (300 μg/l) of inorganic forms is indicated from the data obtained. However, it should be pointed out that extensive algal growths were produced under laboratory conditions with plentiful supplies of phosphorus and deficient supplies of nitrogen. Undoubtedly, nitrogen fixation, either bacterial or algal, bridges the deficiency and produces the nitrogen necessary for the synthesis of algal protein. In the absence of plentiful supplies of phosphorus, however, nitrogen fixation was found to be unimportant."

In contrast, Hutchinson[18] in *A Treatise on Limnology*, Volume I, reports nitrogen values of from 50 to 85 micrograms per liter in three Wisconsin lakes that produced regular nuisance blooms of algae. Gerloff and Skoog[19] in "Nitrogen as a Limiting Factor for the Growth of *Microcystis aeruginosa* in Southern Wisconsin Lakes" found that an N/P ratio of 60/1 is optional to produce growth, although the N/P ratio as it occurs in algae is 10/1. This reduction is confirmed by Strickland[20] who states, in "Measuring the Production of Marine Phytoplankton," that if nitrogen is present in excess, algae can develop with a phosphorus content of only 20 percent of its normal value. The usual phosphorus content of algae averages 1 percent of the dry cell weight. The ability of algae to grow in the presence of suboptional concentrations of nitrogen and phosphorus complicates the problem. The nutrient requirements in an impoundment environment with respect to nitrogen and phosphorus are further complicated by the recycling of nutrients caused by death and disintegration of algae. This is reported by Mackenthun[21] in "The Effect of Nutrients on Photosynthetic Oxygen Production in Lakes and Reservoirs." Another complicating factor is the nitrogen fixation ability of many algae, which is reported by Sawyer, Ferullo, Dugdale, and Neess[22] in "Algae and Metropolitan Wastes" and by Sawyer.[17] The varying nitrogen and phosphorus requirements of different species of algae are also a complicating factor.

Finally, there is the problem of other nutrients that these organisms require. Lackey[22] states, "When we note the condition of blooms in the field, it is at once apparent that there is much variation of the conditions under which they appear, and at best, our knowledge of what nutrient substances and amounts are related to algal densities, is merely a guess." Later, referring to *Euglenophyceae*, he states, "However, for these last, it is highly probable that undefined extractives and dissolved organic substances (often from the excreta and dung of animals) are also necessary." Finally, he remarks, "There has been considerable discussion of the possibility of removing PO_4 from the effluents of conventional treatment plants. It is suggested here that this may change only the composition of the bloom. There are algae whose PO_4 requirements are extremely low, below the concentration which might remain after treatment."

In the same report, Provasoli[22] discusses the vitamin requirements of algae. In a table listing 154 species of algae, he notes that 98 have a vitamin requirement. He further states, "The above data clearly indicate that B_{12}, Thiamine, Biotin, and perhaps other unknown growth factors are ecological factors which we cannot afford to neglect." Extensive marine ecology literature notes vitamin B_{12} as an algal growth stimulant. Rodhe,[23] reporting on the inorganic requirements of algae in "Environmental Requirements of Fresh Water Plankton," states that iron, magnesium, and potassium all influence the growth and development of algae in a manner similar to that exercised by nitrogen and phosphorus. Goldman[24] found molybdenum a limiting factor in Castle Lake, California,

and one or more trace elements limiting in the lakes of Alaska and New Zealand. In addition to these requirements, diatoms have a specific requirement for silica.

In a personal communication, Mackenthun of the U.S. Public Health Service stated that the situation in Lake Wingra, in Wisconsin, is one of ample nitrogen and phosphorus concentrations. In spite of this, a balanced and controlled algal growth, rather than a nuisance bloom, has developed. The possiblity of a growth factor's being missing in this situation cannot be overlooked. In a personal communication, Maloney of the U.S. Public Health Service said that the precipitation of iron (as iron sulfide), because of the formation of hydrogen sulfide in lake waters, prevents continued algal growth owing to a lack of iron. Iron must, therefore, be another trace nutrient. These five reports indicate how truly complex the nutrient requirement problem is. Although considerable research work has been done, this problem, is not yet completely understood.

It must be remembered that algae provide an important link in the overall food chain. Difficulties arise only when these organisms become extremely out of balance, and a bloom occurs. These difficulties are well summarized in a paper by Mackenthun ,[21] pertinent extracts are given in the following quotation:

> "Enrichment often results in domination of the algal mass by a relatively small group of blue-green algae which becomes well established. . . . Fish kills have resulted from supersaturation of oxygen, as well as depletion of oxygen. . . . When algal cells die and sink to the hypolimnion, oxygen is used in their decomposition. . . . Fishing may be impaired. Bathing, boating, and water skiing often are indefinitely postponed in waters which otherwise would offer maximum multiple recreational use. Industrial and municipal water treatment is hampered and made ineffective by extensive aquatic growth; property values are lowered, and often resort trade is cancelled as a result of these nuisances. . . . Rapid decomposition of dense algal scums with associate organisms and debris gives rise to odors and hydrogen sulfide gas, which creates strong citizen disapproval and often stains the white paint on residences adjacent to the shore."

Another useful summary of the overall problem is contained in "Stream Pollution by Algal Nutrients" by Stumm and Morgan.[25]

Hasler[26] is another investigator who has written extensively on this subject. In his article "Eutrophication of Lakes by Domestic Drainage," he summarizes the problem by citing to Lake Zurich in Switzerland. This lake is composed of two basins separated by a narrow passage. Less than 100 years ago both basins were clear and clean. About 1895, however, the lower basin began to receive urban drainage from several towns with a total population of about

110,000. The City of Zurich does not contribute wastes to the lake, although it is along the shores.

Shortly thereafter, problems developed. To quote Hasler:

> "Hand in hand with the increased urban fertilization there developed (beginning in 1896) algal scums, malodorous and displeasing to the eye. The lake ceased to be an attractive site for general vacationing, boating, and bathing. Moreover, since the cities and their industries got their water from the lake, expensive filtering and purifying systems had to be installed to remove the greatly increased mass of organisms and their accompanying obnoxious odors and flavors. . . . The shallower of the two lakes, the Obersee, which receives no urban drainage, changed little and still retains its 'virgin' lake characteristics."

The problems that developed in the lower basin of Lake Zurich constitute a classic example of accelerated eutrophication because the Obersee remained clear and serves as a control for comparison.

Research Needs

For a better understanding of the relationship between eutrophication in natural waters and development of algae, the true nutrient requirements of some of the more common species of problem algae must be established. The nutrients might be determined by growing algae in a simple well-defined medium in which growth factors and inorganic trace elements could be varied independently. Through such a systematic investigation, the true nutrient requirements of the various algal species could be evaluated. These laboratory data should then be taken to field situations, such as Lake Wingra, to demonstrate an understanding of the cause of the unexpected behavior.

Many competent investigators are well aware of the needs in this area and have been working toward a complete definition of these nutrient requirements. Examples of investigators in this area are a group of General Dynamics Corporation scientists, Kettering Laboratory scientists, and Drs. Skoog and Gerloff at the University of Wisconsin. The occasional unexpected behavior that occurs in the field indicates, however, that all facets of algae nutrition are not yet known.

Two other factors must be considered as part of the eutrophication problem, algae-destroying viruses and algal toxins. Algal viruses have been isolated, and their algae-destroying properties are described by Safferman and Morris[27] in "Control of Algae by Viruses." The existence of algal toxins are thus far speculative, but in the late fall of 1963 the algal counts in the Markland Pool of the Ohio River at Cincinnati were well below the expected level, in view of the quality of the water at that time. One possible cause of this could have been algal toxins.

Two recent articles discuss techniques that may prove useful in the suggested studies on the effects of nutrients and toxins on the development of organisms. Goldman[28] in "A Method of Studying Nutrient Limiting Factors *In Situ* in Water Columns Isolated by Polyethylene Film" describes a static test in which a long, large isolated column of water was inoculated with a given material and the influence of that substance on the water column determined by comparison with the behavior of the external water. In their paper "Further Measurements of Primary Production Using a Large-Volume Plastic Sphere," Antia, McAllister, Parsons, Stephens, and Strickland[29] describe a similar technique, except that their apparatus is free floating and continually mixed, because of rotation. Both of these techniques are interesting and potentially helpful.

LIGHT PENETRATION AND TURBIDITY REMOVAL

Existing Information

Limnologists have given considerable attention to the effects of light intensity on the development and growth of algae. Varma and Wilcomb,[30] in an article entitled "Effect of Light Intensity of Photosynthesis," show a direct relationship between light intensities and photosynthetic rates. Optimum light intensities are not, however, necessary as Verduin[31] points out in "A Discussion of 'Biochemical Degradation and Photosynthetic Oxygen Production in Reservoirs"; less than 2 percent of the optimum light intensity supports a healthy algal bloom. Light intensities above the optimum are actually detrimental to algae, as Vaccaro and Ryther[32] point out in their article "The Bactericidal Effects of Sunlight in Relation to 'Light' and 'Dark' Bottle Photosynthesis Experiments." They also state that if water is brought from some depth to the surface, placed in containers, and returned to the original depth, the algae may be injured by being subjected to a high light intensity during the trip to the surface. This also has an influence on the behavior of algae that are being mixed vertically. This type of mixing results in the continual movement of the algae from positions of low light intensity to those of high light intensity.

Metzler's[33] paper "Improvement of Water Quality in Kansas" was the only one found that specifically notes that the decrease in turbidity in impoundments caused increasing productivity, but he reports this only in a qualitative manner. Churchill of TVA, as noted in a private communication, and Neel, Nicholson, and Hirsch[8] measured the reduction in turbidity caused by impounding waters. In the TVA's Cherokee Reservoir, reductions in turbidities from 40 to 60 Jackson units in the influent to 10 or less in the effluent were quite common throughout the year-long study. In the Fort Randall Reservoir on the Missouri River, reductions in turbidities from 400 to 500 Jackson units to less than 35 were measured over a 6-month period. All other conditions being the same, this clarification of the river waters causes potential problems. Dvihally,[34] in

"Transformation of Energy in Inland Waters Examined on the Basis of Investigations Carried out Using Modern Physico-chemical Methods," relates the penetration of certain wavelengths of light in different quality waters to the productivity level of the water. In one case, waters with relatively large sodium concentrations allowed the penetration of red light, the most favorable for photosynthesis, whereas in the waters of another river the wavelengths of light that reached the deeper layers were ineffective from the point of view of photosynthesis. He concludes, therefore, that, "The transformation of energy therefore depends on the turbidity of the water, adsorption of light, and spectro-composition."

Research Needs

The prime research need is to relate quantitatively the reduction of turbidity and the increased penetration of light caused by the relatively long detention times in impoundments to the increased productivity of these bodies of water, since this is potentially a serious problem. Although this relationship is noted by Metzler,[33] it has never been specifically measured in, for example, a newly created impoundment. This needs to be investigated both with laboratory and field studies. The Pearl River Impoundment Project[35] is to measure water quality in a newly created impoundment before (river water quality) and after (impounded water quality) construction of the dam. These data may help satisfy this need. Further attention should also be given to the practicability of reducing productivity by blocking light with coverings such as powdered carbon or floating polystyrene.

OXYGEN PRODUCTION AND DEMAND

Existing Information

The measurement of oxygen production by plankton has been of considerable interest to both limnologists and sanitary engineers, although limnologists are generally more interested in primary production of new organism mass than in oxygen production. Many articles in the limnologists' literature discuss methods of measuring primary production and methods for eliminating the complicating feature of simultaneous oxygen production and organism respiration. When dealing with an impoundment, the sanitary engineer is interested in the net effect of the algal population in the oxygen balance, rather than the gross production of oxygen by the algae. A study on the Truckee River by O'Connell, Thomas, Godsil, and Hirth[36] is a good example of an attempt to measure the net rather than the gross influence of plankton on oxygen concentrations.

Verduin[31] summarizes much of the limnological literature on this topic and suggests that the gross photosynthetic rate for an average algal density is 16 grams of oxygen per square meter per

day. For a 10-meter euphotic zone (the depth in which 99 percent of the incident light is absorbed), this amounts to 1.6 milligrams of oxygen per liter per day. He points out, however, that the daytime respiration of these organisms consumes one-half of the gross photosynthetic oxygen production. Other worthwhile articles in this general area are "Primary Production in Flowing Waters," by Odum[37] and the review "Measuring the Production of Marine Phytoplankton" by Strickland.[20]

The oxygen production by algae in connection with waste stabilization ponds has interested sanitary engineers for many years. A summary of typical waste stabilization pond experiences was given by Towne, Bartsch, and Davis[38] in 1957. Of even greater interest to those studying impoundment behavior is the work of Hull, however. Hull compares the rate of photosynthetic oxygen production with the surface reaeration in Baltimore Harbor in "Oxygenation of Baltimore Harbor by Planktonic Algae,"[39] and the Delaware River in "Photosynthetic Oxygenation of a Polluted Estuary"[40] through the use of the "light" and "dark" bottle technique. Although this technique is criticized by Pratt and Berkson[41] in "Two Sources of Error in the Oxygen 'Light' and 'Dark' Bottle Method," Verduin[42] in "Energy Fixation and Utilization by Natural Communities in Western Lake Erie," and Kaplovsky[43] in "Discussion of 'Photosynthetic Oxygenation of a Polluted Estuary'," and the problems with this technique are summarized by Strickland,[20] these studies still give the most direct indication of photosynthetic activity. Hull has used the method, with reservations concerning its accuracy, to show the general significance of photosynthesis in the oxygen balance of polluted waters.

In the Baltimore Harbor work, Hull[39] calculates that in the summertime the algae produce 600,000 pounds of oxygen per day whereas atmospheric reaeration at the air-water interface provides only 187,000 pounds per day. He also refers to studies of Nusbaum and Miller conducted in San Diego Bay. They calculated the ratio of photosynthesis to atmospheric oxygenation as 1.35/1.

In the Delaware River studies, Hull[40] states that August is the critical month with respect to oxygen resources. The mean photosynthetic oxygen contribution, calculated from 16 measurements during the month, was 1,789,000 pounds per day, which Hull feels is a low estimate. He feels that the maximum rate obtained, 3,893,000 pounds per day, is really more representative of the photosynthetic production on a sunny August day. Since the oxygen demand in the river during the same period was calculated as 3,260,000 pounds per day, the atmospheric reaeration must have been somewhere between 45 and 0 percent of the total demand, depending on the actual photosynthetic contribution.

Hull's general thesis in all of his writings is that photosynthetic oxygen is a source of oxygen that has long been overlooked and/or neglected by sanitary engineers. This concept is expressly contained in a discussion by Hull[44] of a paper by O'Connor on reoxygenation of water.

In some instances photosynthetic activity is so vigorous that the upper layers become supersaturated, and oxygen is lost to the atmosphere. An analysis of Roanoke Rapids Reservoir by Pritchard and Carpenter, included as an appendix in the report by Fish, Hull, Peters, and Knight,[45] shows a loss of 1.0 gram of oxygen per square meter per day to the atmosphere. Hull[46] analyzed the same data by a different technique but with the same result. He concludes:

> "There appears to be a need for study to find ways of capturing the oxygen lost to the atmosphere. Perhaps mechanical mixing of the reservoir water to prevent supersaturation at the surface is one method of retaining and using for waste decomposition the oxygen now lost to the atmosphere. If the average surface oxygen concentration can be reduced by this means to values significantly below saturation, the atmosphere will become an additional oxygen source instead of an oxygen sink."

Attention has also been given in the literature to the oxygen demand of the algal population in water. This demand takes three forms: (1) respiration that occurs while photosynthesis is progressing, (2) respiration that occurs at night when photosynthesis is absent, and (3) the oxygen uptake caused by consumer organisms, mainly bacteria, that metabolize the algal bodies upon their death.

As mentioned above, Verduin[31] suggests that the daytime respiration is about one-half of the gross photosynthetic rate. In the same article he also states that the balance between the net daytime photosynthetic rate and the nighttime respiration of the algal community is fairly close. This means that if all of the algae stayed in the upper waters of an impoundment, the net 24-hour contribution to the oxygen balance would be near zero. Because many algae fall from the euphotic zone during a given 24-hour period, however, the dark respiration, and/or the oxygen uptake because of bacterial decomposition, does not occur in the surface waters. The net increase in oxygen concentration is, therefore, often in the surface waters because of algal action, since the major portion of the oxygen demand takes place in the bottom waters or in the bottom muds.

Several investigators have discussed this problem. Mackenthun[21] quoting Renn, states, "The nutrients' stimulation of algal production can lead to the formation of a mass of organic matter greater than that of an original waste source." Knopp[47] in "The Influence of Plankton on the Oxygen Demand of River Water" shows that an error of more than 50 percent in the overall balance might occur if the oxygen demand caused by the decomposition of algae were neglected. Thomas[48] in his article on "Oxygen Deficit Rates for the Central Basin of Lake Erie" discusses the measured rate of oxygen depletion in the hypolimnion of central Lake Erie. He found that this rate was 0.037 milligram per square centimeter per day and that this was very close to the maximum possible rate that could be sustained and still maintain dissolved oxygen throughout the hypolimnion during the stagnation period. This demand was partially

caused by the decomposition of algae in the lower waters of the lakes. Edmondson[49] in his article "Secondary Production and Decomposition" also addresses himself to the problem of the growth of consumer organisms in lakes and the oxygen demand caused by these organisms.

Hull's[46] position is summarized in the following quotation:

> "I have been frequently reminded that for every gram of oxygen released by photosynthesis, a gram of biochemical oxygen demand is produced by the synthesis of organic matter, and therefore there can be no net gain of oxygen. This is a gross oversimplification—it must be qualified by consideration of the relative rates, periods, and locations of the oxygen liberation and subsequent oxygen demand. To support this, one need only point to the vast standing crop of fixed carbon on this earth in the form of petroleum, coal, plants, and animals, including several billions of human beings. All of this carbon was fixed by photosynthesis, but some of it has waited millions of years to be oxidized, before it will eventually take back the oxygen liberated at its birth."

Research Needs

Two quotations from the literature indicate the research needs in this area. Mackenthun[21] states, "There is a need to relate photosynthetic oxygen production to: (1) practical problems associated with lakes and streams, (2) some quantitative expression of phytoplankton, (3) nutrient balance, and (4) seasonal fluctuations and climatic phenomenon." Verduin[50] in "Photosynthesis by Aquatic Communities in Northwestern Ohio" remarks, "Any attempt to correlate metabolic rates under natural conditions with environmental factors (nutrients, temperature, light supply, etc.) yields 'shotgun results'."

The overall role of algae in the production of oxygen and the oxygen demand of impounded waters, as related to the environment, must be determined if the behavior of impounded waters is to be completely understood. Past studies must be extended in scope to include the production of oxygen in surface waters, the demand for oxygen in lower waters, and the transfer of oxygen at the surface so that the entire oxygen balance of an impounded body of water is truly measured. Although the light- and dark-bottle technique has its disadvantages, this method is an attempt to actually measure *in situ* oxygen concentration changes. Some method must be developed to overcome the difficulty of unnatural conditions that occur in glass bottles, e. g., the lack of mixing. Also, these data must be taken over a short enough period of time so that the environmental conditions, sunlight, water temperature, wind velocity, and so forth, will be steady during the time the measurements are being taken. Only through this technique can the influence of algae on the oxygen

balance of impounded water, as related to the environment, ever be determined. This determination must be made, for surely the relationships between algal development and the environment are not as haphazard as would be suggested by Verduin.[50] A study designed to develop equipment to make these measurements with the use of dissolved oxygen probes has begun in the Engineering Section at the Robert A. Taft Sanitary Engineering Center.

CARBONATE EQUILIBRIUM

Existing Information*

Since algae remove carbon dioxide from solution as they grow and convert it into cellular material, the carbonate equilibrium as it exists in natural waters is affected. Some unpublished work by Sawyer shows why the pH attained in natural waters by algae can exceed 7. He has observed values as high as 9.8 where algae are in high concentration and under favorable light conditions. The equilibria involved are shown in equation 1.

$$(2\ HCO_3^- \leftrightarrows CO_2 + [CO_3^{=} + H_2O) \leftrightarrows HCO_3^- + OH^-] \qquad (1)$$

When carbon dioxide is removed, the primary equilibrium shown in parentheses ( ) shifts to the right and the carbonate ion concentration increases. An increase in carbonate ion concentration, however, effects the secondary equilibrium, shown in brackets [ ]; the secondary equilibrium also shifts to the right and the hydroxide ion concentration increases. The pH, therefore, rises to levels considerably above 7. A ceiling on pH is formed by precipitation of calcium carbonate that controls the amount of carbonate ion that can coexist in solution with calcium ion.

Neel, Nicholson, and Hirsch[8] also discuss this same set of equilibria. They point out that carbonate precipitation is common in standing bodies of water and has been responsible for commercially important marl deposits in natural lakes. They also note that the transformation of bicarbonate to carbonate ions occurs in upper layers of the water and that in a stratified impoundment the precipitated carbonate particles dropping down into the hypolimnion may or may not reach the bottom. This is because the hypolimnion generally contains relatively higher concentrations of carbon dioxide because of the biological activity that has occured in these waters during the decomposition of falling algal bodies and because of the absence of many viable algae in the hipolimnion. The precipitated carbonate particles combine with this carbon dioxide and are converted into soluble bicarbonates that increase the alkalinity of the deeper waters. With these relationships in mind, these investigators measured, reported, and discussed the changes in alkalinity and in hardness that occurred in the six reservoirs on the Missouri River.

Limnologists have often shown an interest in the carbonate equilibrium in natural waters because of the possibilities of measuring

* See: C. N. Sawyer, Chemistry for sanitary engineers. McGraw-Hill Book Company, Inc., New York, N.Y., 1960. 367 pp.

W. J. Weber, Jr., and W. Stumm. Mechanism of hydrogen ion buffering in natural waters. JAWWA. 55:1553-1578. Dec. 1963.

primary production by the change in carbon dioxide concentration in the waters. Verduin[42] is very enthusiastic about this procedure, feeling that this is the only method to measure primary production in unconfined waters. He further states that measurement of photosynthetic rates in unconfined waters is the only method of obtaining the true rate. In his opinion, whenever a sample of water is enclosed in a container, it no longer represents the natural environment, and measurements of the sample, therefore, do not represent natural photosynthesis.

For example, the gross photosynthetic rate of 16 grams of oxygen per square meter per day measured in unconfined water, as cited by Verduin,[31] is much greater than the rate of 2.25 grams per square meter per day that Hull[46] reports in the upper 0.5 foot in the Delaware River Estuary at 20°C. These data are from light- and dark- bottle experiments. Hull states that this value is related to temperature, however, and at 30°C he gives a rate of 21 grams of oxygen per square meter per day.

Research Needs

Research in this area is important, since changes in the carbonate equilibrium can cause either the precipitation of hardness-causing ions, the reduction of alkalinity, or under reverse conditions the dissolution of carbonates from the impoundment bed. Any complete understanding of the behavior of impounded waters should include some knowledge of the influence of microorganisms, both algae and bacteria, on the carbonate equilibrium. Some of the studies mentioned above, designed to relate the growth of an algal population to a specific environment, should also include studies on the carbonate equilibrium in the same environmental circumstances.

NUTRIENT REMOVAL

Existing Information

Since algae require nitrogen and phosphorus to build new protoplasm, they take these nutrients from solution during their growth cycle. This is also true of other nutrients, but to a smaller extent; therefore, these will be neglected for the moment. If the algae are removed from the water before they die, decompose, and release the nitrogen and phosphorus back into solution, these troublesome fertilizing elements will not be available for subsequent generations of algae. Since nitrogen is generally present in more abundance than phosphorus, and because of the nitrogen-fixing properties of many algae,[17,22] the possibility of removing phosphorus from solution through algal growth has been given the greatest consideration in the literature. Sawyer[17] suggests that at least 15 micrograms of phosphorus per liter of water is necessary for algal growth. This implies that if algae were used for phosphorus removal, the concentration could not be reduced below this minimum level. Hutchinson,[18] however, states, "Some organisms, such as *Asterionella*,

in natural lake waters are extraordinarily efficient in the utilization of the element phosphorus and can take it up from water containing less than 1 µg/l." Lackey,[22] quoting Yount, states, "Young (1955) concludes that, 'there is, in any habitat, no one factor which determines the species density of an area, but always a combination of factors.'" This means that in any nutrient removal scheme there is the possibility that a combination of factors rather than the concentration of a specific nutrient of interest may limit the population density. This would interfere with a specific nutrient removal scheme.

The combination of factors may or may not be a serious problem. Liebig's Law of the Minimum[51] suggests that the quality of the least abundant nutrient relative to the requirement for that nutrient controls the maximum development of a culture, irrespective of the concentration of any of the other nutrients. This means that a group of organisms will grow to some limit imposed by the nutrient in least relative supply for that group, even though the water might be richer in many other nutrients. Even if this group of organisms were removed, a new group could grow in this water because of different nutrient requirements. Therefore, the original nutrient removal attempt would not necessarily protect the impoundment against all further algal blooms.

Some attention has been given to the removal of nitrogen, phosphorus, or both in waste stabilization ponds. Bogan[22] found that algae were effective in removing phosphorus from sewage. In a high-rate controlled laboratory experiment, however, the extremely rapid rates of phosphate removal were caused more by a rising pH and corresponding precipitation of calcium phosphate than by metabolic uptake. In summary, he states, "Adsorption and coagulation appear to play a major role where rapid removal of large amounts of phosphate is involved (in the high-rate laboratory experiments). Metabolic conversion is the principal removal mechanism under the more leisurely conditions prevailing in oxidation ponds and sewage lagoons. In the latter case (oxidation ponds), efficiency of phosphate removal is proportional to detention time, other things being equal." Note, the parenthetical phases have been added.

Gates and Borchardt,[52] authors of "Nitrogen and Phosphorus Extraction from Domestic Waste Water Treatment Plant Effluents by Controlled Algal Culture," have also studied the removal of nutrients from secondary sewage effluent. They included studies on both nitrogen and phosphorus in their research. They investigated performance as related to four variables: (1) culture depth, (2) light intensity, (3) nutrient concentration and (4) culture density.

They found mixing and maintaining an algal concentration to nutrient concentration of 4 to 1 beneficial in the removal of nutrients. As this ratio increases because of nutrient utilization, the rate of removal decreases, however, so that the degree of treatment and the time required for treatment are not linearly related. In spite of this useful research the authors realize more study is needed since they close their article with this comment: "Areas which need considerable attention are: separation techniques for algae; techniques for utilizing

waste algae; further temperature, depth, and light relationships; the capability of algae to extract trace elements; and the engineering development of mechanisms for the production of light integration."

Hicks,[53] in 1958 reviewed the methods available for harvesting algae from water. He investigated centrifugation as well as coagulation with alum and acid. Some studies were also made on the anaerobic digestion of the harvested algae. He concluded, "At present there appears to be no commercially sound scheme for harvesting the algae." Bogan[22] also referred to the problem of harvesting algae. He mentioned screening, settling, centrifuging, and chemical coagulation. In summary he states, "All have been found wanting in some aspect, generally in terms of efficiency and often in terms of cost. From the standpoint of performance and economy, some type of screening device appears to be the most promising." This comment agrees with some of the European experiences using floating microstraining devices, such as those developed by Glenfield and Kennedy, Inc.

Oswald[54] in his article "The Coming Industry of Controlled Photosynthesis," which summarized 10 years of his research in the area of growing algae on sewage, states. "Nevertheless, the fundamental findings of the past 10 years are unmistakable. It is technically feasible to apply controlled photosynthesis to treat wastes, to reclaim water, to render waste organic matter suitable for use as an animal feedstuff, to obtain unprecedented yields of protein per acre of pond surface in either fresh or saline water, and to produce electrical power from sunlight using organic wastes as a medium." He goes on to remark, however, that in spite of the present technical feasibility of harvesting algae, more research needs to be done to improve the economics of this step of the process.

Research Needs

The research needs in this area center on three points: (1) determination of how efficient a nutrient removal scheme under lake conditions can be, (2) the most effective way of harvesting the algae, and (3) destruction of harvested algae. Laboratory experiments on the growth of algae and their subsequent nutrient removal in lake waters would supply information pertinent to the first point. The harvesting studies comparing existing equipment, with possible modifications, under field conditions would contribute to the second. Some useful information on the ease of destruction of harvested algae could be obtained on a laboratory or small pilot scale. Laboratory, small pilot plant, and field studies on this topic would indicate whether the growing of algae themselves could be an effective method of removing fertilizing nutrients and preventing further growth. Stimulation of fish life might be an area worth exploring as an algae removal method. Another possibility is removing or covering the upper layer of bottom mud, which is usually rich in settled phosphorus, to prevent this nutrient from being recycled into the euphotic zone.

Inorganic Substances

DISSOLVED OXYGEN

Existing Information

The behavior of the dissolved oxygen concentrations in polluted streams has received considerable attention through the years. This attention started with the classic work of Phelps[55] in 1912 and of Streeter and Phelps[56] in 1925. Their work has been reviewed, and modifications have been suggested by various investigators, such as Fair[57] in 1939; Hull[58] in 1960; O'Conner and Dobbins[59] in 1956; Krenkel and Orlob[60] in 1962; and Churchill, Elmore, and Buckingham[61] in 1962. A useful summary was published in 1958 by the U. S. Public Health Service, "Oxygen Relationships in Streams."[62]

Unfortunately, similar active interest has not been shown in the dissolved oxygen relationships in impoundments. The role of algae is discussed earlier in this report; Hull,[39,40] and Vinberg and Siviko[63] are some of the investigators who have reported on this subject. As stated previously, however, although algae may produce a net increase in dissolved oxygen concentration in surface waters, their decomposition in deeper waters, with a corresponding oxygen uptake, means that the net gain in the oxygen resources of the impoundment is reduced, as noted by Mackenthun.[21]

Even less attention has been given to the atmospheric reaeration capacity of slowly moving or standing bodies of water. Hull[39] calculated this contribution for one set of circumstances in Baltimore Harbor, and Kittrell[64] in his article "Effects of Impoundments in Dissolved Oxygen Resources" states that the atmospheric reaeration rate in impoundments is low, but he gives no numerical values for this rate. He does state, however, that in spite of this low rate, the pounds of oxygen transferred through this mechanism may be substantial because of the long detention time. This article is an excellent review of this situation and contains a valuable bibliography.

The existence of low dissolved oxygen in the bottom waters of stratified impoundments has been reported repeatedly since the classic work of Birge and Juday[65] in 1911. Often, this water occurs in impoundments used for peaking hydroelectric power generation. Periodically, a large quantity of water having a low dissolved oxygen concentration is released from these impoundments through the turbines. The problems caused by these releases are discussed by Ingols in "Pollutional Effects of Hydraulic Power Generation"[66] and "Effect of Power Impoundments Upon Downstream Water Quality."[67] He points out, that although this low dissolved oxygen concentration water reduces the downstream dissolved oxygen concentration, it does not necessarily reduce the number of pounds of oxygen downstream because the latter depends upon both volume and concentration. The oxygen-deficient water may well put a burden on the downstream fish population, as well as on a downstream industry or municipality that depends upon the stream for waste assimilation.

Since the problem of releasing water with a low dissolved oxygen concentration through hydroelectric generators has been recognized for some time, various remedial measures have been proposed. Scott, Wisniewski, Lueck, and Wiley[68] in "Aeration of Streamflow at Power Turbines" and Bueltman, Termini, and Kingsbury[69] in "Power Requirements for Oxygen Transfer with Turbine Aerators" discuss methods of introducing oxygen into the turbines of the power generators. Although the efficiency of electric power generation would be reduced slightly, these authors feel that adding oxygen at the turbine is fairly economical.

In another method, being tried at two impoundments on the Roanoke River, a submerged weir about 400 feet upstream from the power intake is supposed to block the flow of hypolimnion water to the power intake and permit the flow of top waters to the turbines. This installation is discussed in detail by Fish, Hull, Peters, and Knight[45] and by Ragone and Peters.[10]

Olszewski[70] in "Experiment on Drawing Off the Hypolimnic Water from a Lake" reports on an experiment in Lake Kortowo in Poland in which the surface outflow was cut off and the resulting increased flow in the epilimnion was used to force the hypolimnetic water out of the basin.

Some proposals have been made for reaerating the stream below a dam. Another method suggested is mixing of the entire reservoir contents. A detailed discussion on this possibility will be given later. Multilevel outlets are discussed by Kittrell;[64] these are effective, but expensive.

Research Needs

The oxygen budget of standing bodies of water must be re-evaluated, first to understand what mechanisms of oxygenation and deoxygenation are involved, and second to understand how the environment affects the overall budget. Hull[71] in his "Second Progress Report of 'Low-Flow Augmentation for Stream-Pollution Abatement' Project" reports on a model that was constructed to study atmospheric reaeration in the laboratory. A useful method of studying the behavior of dissolved oxygen at the mud-water interface was described by Fremling and Evans.[72] As previously mentioned, the Engineering Section at The Robert A. Taft Sanitary Engineering Center has begun a field investigation designed to measure more reliably both atmospheric reaeration and photosynthetic contribution in the upper waters of impoundments.

NITROGEN

Existing Information

A very complete discussion of the nitrogen cycle in lake waters is given in chapter 16 of *A Treatise on Limnology* by Hutchinson,[18] and all of the reactions are summarized in Figure 1. In spite of the thoroughness of this review, many of the data quoted, in Hutchinson's opinion, remain only partially explained. For example, in discussing

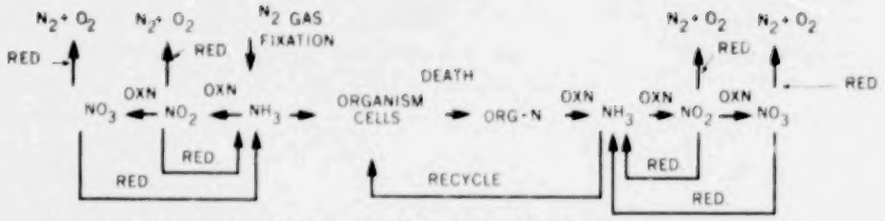

Figure 1. Summary of nitrogen cycle, after Hutchinson (see Ref. 18).

data taken by Mortimer in England, which showed a sudden change in the nitrogen balance of a given lake, Hutchinson states, "The most reasonable, though not entirely satisfactory, explanation of the phenomenon apparently indicated by Mortimer's results is that at the time of circulation, when the water is oxygenated throughout the lake, the formation of an oxidized microzone permits adsorption of ammonia from the water, and that later this adsorbed ammonia is nitrified and liberated into the lake." Later, in discussing similar data taken by Yoshimura in Japan, he remarks, "It is conceivable that a compensating fall in nonalbuminoid organic nitrogen occurred, either in solution or in the seston, or that the results are due to denitrification or nitrogen fixation. Neither hypothesis, however, seems very likely."

Hutchinson makes this comment on nitrogen fixation, "It has become apparent that certain blue-green algae are important nitrogen-fixing organisms, and in the case of the genus *Anabaena* there is good reason for believing that such algal fixation is of significance in those lakes in which the genus occurs abundantly." He also lists other nitrogen-fixing algae.

One of the investigators who reported in "Algae and Metropolitan Wastes," Dugdale,[22] along with his coworkers, has been studying intensively the phenomenon of nitrogen fixation in lake waters for many years. Authors in numerous publications feel that nitrogen fixation is a very common and widespread phenomenon in lake waters.

In his summary Hutchinson states that, "Ammonia is produced by practically all heterotrophic bacteria in the course of organic decomposition. At least in some lakes, nitrification can take place in the free water whenever oxygen is present, whereas nitrate reduction occurs at all times. Nitrification appears to proceed most rapidly in winter and nitrate reduction in summer. The existence of denitrifying bacteria that liberate molecular nitrogen is known, but it seems probable that most of the nitrate reduced forms ammonia." Several investigators feel that denitrification is of more importance than Hutchinson implies. Schmidt and Kampf[73] in studies in surface waters, Johnson and Schroepfer[74] in activated sludge studies, and Cooper and Smith[75] in soil studies have all demonstrated significant losses of nitrogen gas during nitrate reduction. There can be no doubt that nitrate is reduced to ammonia when the nitrogen is required for new cell synthesis; but when nitrate is reduced for oxygen, the end product is gaseous nitrogen. Finally, to complete Hutchinson's summary, he states, "Nitrite and hydroxylamine are

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known to occur in lakes, as intermediates in the oxidation or reduction processes."

Most of the reports on which Hutchinson based his writings were not concerned with the nitrogen balances - probably because nitrogen balances are so difficult to make. He does quote one study by Rohlich and Lea in 1949 in which they calculated that 155.8 metric tons of total nitrogen came into Lake Mendota during a 12-month period, and only 41.4 metric tons of total nitrogen left the lake; thus 114.4 metric tons of nitrogen was not accounted for. This could be caused by denitrification or the settling into the mud of organic nitrogen. If the latter were true, this nitrogen would be available for recycling.

A recent paper by Leclerc,[76] "Self-Purification of Fresh Water Streams as Affected by Temperature and by the Control of Oxygen, Nitrogen, and Other Substances," also makes note of the inability to make nitrogen balances in surface waters. He states that rivers receiving normal quantities of sewage self-purify rapidly, but the nitrogen balance in them is incomplete. Later he says that if the total quantity of nitrogen contained in the organic materials discharged to streams were to yield ammonia, and if all this ammonia were to be transformed into nitrite and nitrates, these forms would be much more abundant in streams. He then goes on to suggest a rather novel mechanism for loss of nitrogen gas. He suggests the following reaction between nitrites and amino acids:

$$R\text{-}NH_2 + HNO_2 \rightarrow ROH + N_2 + H_2O \qquad (2)$$

The more common explanation for the lack of a nitrogen balance is the reduction of nitrate to yield nitrogen gas and oxygen, although the uncertainty in the nitrate-nitrogen determination by the phenoldisulfonic acid method may well be the explanation for many of the poor nitrogen balances obtained through the years. In addition to the work in rivers extensive work on the biological transformations of nitrogen in the activated-sludge process has been done by Symons and his coworkers.[77,78,79,80]

Research Needs

The research needs in this area fall into four categories: (1) analysis, (2) measurement of cycle balances, (3) measurement of the effect of the environment on the cycle balances, and (4) rate and extent of nitrogen transformations in a given impoundment. Many analytic problems must be solved before the researcher is confident that he can measure all forms of the nitrogen occurring during the study of these cycles. True nitrogen balances must be measured, for only through the measurement of a nitrogen balance can the investigator be assured that all of the nitrogen has been accounted for at any given time. Once a nitrogen balance can be made accurately, the influence of the environment on this cycle must be investigated. Finally, the effect of the biological transformations of nitrogen must be measured in terms of the other quality characteristics in impounded waters.

For example, very little attention has been given to the oxygen demand that the nitrification of ammonia creates. Since the ultimate BOD of ammonia is 4.57 milligrams per milligram, nitrification could severely tax the oxygen resources of an impoundment or stream. The article by Courchaine[81] entitled "The Significance of Nitrification in Stream Analysis - The Effects on the Oxygen Balance" showed that in the particular instance under investigation, nitrification accounted for more than one-half of the total oxygen demand. Laboratory studies have been started in the Engineering Section at Robert A. Taft Sanitary Engineering Center on all phases of the nitrogen cycle.

PHOSPHORUS

Existing Information

Much less controversy revolves around the phosphorus cycle, possibly because it has been studied so much less than the nitrogen cycle. Chapter 12 of Hutchinson's text[18] stands as a prime authority on this cycle. Based on some radiophosphorus experiments within Linsley pond in 1950, Hutchinson summarized the phosphorus cycle as follows:

> "The phosphorus cycle exhibited by these experiments during extreme summer stratification may therefore be considered to involve the following processes.
>
> 1. Liberation of phosphorus into the epilimnion from the littoral, largely from decay of littoral vegetation.
> 2. Uptake of phosphorus from water by littoral vegetation.
> 3. Uptake of the liberated phosphorus by phytoplankton.
> 4. Loss of phosphorus as a soluble compound, less assimilable than ionic phosphate, from the phytoplankton, probably followed by slow regeneration of ionic phosphate.
> 5. Sedimentation of phytoplankton and other phosphorus-containing seston, perhaps largely faecal pellets, into the hypolimnion.
> 6. Liberation of phosphorus from the sedimenting seston in the hypolimnion, or when it arrives at the mud-water interface.
> 7. Diffusion of phosphorus from the sediment into the water at those depths at which the superficial layer of the mud lacks an oxidized microzone."

Research Needs

Although the reactions involving phosphorus are known, the behavior of phosphorus in a specific impoundment is not predictable.

More data from various environments are needed to permit generalization. Analytic techniques, including pretreatment methods, need to be standardized so that all investigators will be reporting the same species of phosphorus. These are six species of phosphorus for consideration: total and soluble orthophosphorus, total and soluble polyphosphorus, and total and soluble organic phosphorus.

SULFUR

Existing Information

The sulfur cycle in lake waters is also uncontroversial, chapter 13 of Hutchinson's text[18] being a very useful summary of the subject. In this chapter he notes that under anaerobic conditions sulfate can be used as a hydrogen acceptor in the metabolic oxidation of organic matter by certain bacteria. Hydrogen sulfide is also produced in the bacterial decay of any organic matter, such as protein, that contains reduced sulfur. This reaction often occurs in the deoxygenated hypolimnion of lakes. Since ferrous sulfide is very insoluble in neutral or alkaline water, however, hydrogen sulfide appears in the free water of the hypolimnion only when the water is acid, or when all of the iron has already been precipitated from solution.

Hutchinson goes on to say that in aerated waters, the bottom muds lose sulfur to the water as sulfate. Therefore, in unstratified waters the sulfate concentration increases with depth. In stratified waters, however, the sulfate concentration decreases in the hypolimnion waters, although a sufficient H_2S concentration may not appear in the free water to account for this decline. The latter phenomenon is due to sulfide precipitation as noted above. He states that possible intermediate products of sulfate reduction, such as thiosulfate, seem to be absent in lake waters. To complete the sulfur cycle, Hutchinson remarks that hydrogen sulfide can be oxidized by sulfur bacteria, which use the oxidation as a source of energy. Hydrogen sulfide can also be oxidized by photosynthetic colored bacteria, which use the gas as an oxygen acceptor in the photosynthetic reaction.

Hutchinson closes his summary of the sulfur cycle by stating that the sulfur budget of a lake may be strongly affected by the inflow of highly mineralized water or sulfur-containing industrial wastes. In the presence of these high inputs of sulfur-containing material, the hypolimnion of a lake can often stimulate the generation of tremendous quantities of hydrogen sulfide. A concentration of hydrogen sulfide of 786 milligrams per liter of water at the bottom of Big Soda Lake, Nevada, has been found under the conditions described previously.

Research Needs

As with nitrogen and phosphorus, analytic problems need to be solved to permit the measurement of all forms of sulfur in low concentrations. Once a sulfur balance can be made, the influence of the environment on it must be measured to allow future predictions. Knowledge of hydrogen-sulfide-producing conditions are

important because hydrogen sulfide in high concentrations may be toxic to the organisms and the discharge of hydrogen-sulfide-laden waters through power dams will cause problems.

IRON

Existing Information

Not too much concerning the iron cycle in impounded waters appears in the literature. Hutchinson[18] treats this matter in chapter 11 of his book, as do Stumm and Lee[82] in their article "The Chemistry of Aqueous Iron." In a section of their paper entitled "Some Limnological Aspects," Stumm and Lee summarize the iron situation in impounded waters. This summary, which draws heavily on Hutchinson, is pertinent to this report. They state:

> "A vast amount of analytical data exists relating to the iron content of inland waters. The uncertainty of analytical techniques used in these investigations is a serious obstacle for the interpretation of the available data. The published analytical techniques do not permit a rigorous quantitative differentiation between ferrous and ferric iron. Furthermore, it is rather difficult to distinguish analytically dissolved and suspended iron.
>
> "Bearing in mind the theoretical conclusion of the solubility equilibria, the available data indicate that a substantial fraction of the iron in many lake waters is present either in suspended form or as an organic iron complex. However, the waters of uncolored neutral or alkaline lakes, which are poor in plankton, have iron contents usually ranging from 50 to 200 μg/l, which appears to be in accord with solubility equilibria. In the epilimnion of such lakes where generally the concentration of dissolved oxygen is high, the concentration of soluble ferric iron cannot exceed 18 μg/l and ferrous iron is unstable in the presence of dissolved oxygen. Any iron which enters the epilimnion will eventually be precipitated as ferric hydroxide. The insoluble ferric iron settles into the hypolimnion.
>
> "Here, in the absence of dissolved oxygen, favorable conditions for the reduction of ferric hydroxide to ferrous iron may prevail. In waters free of oxygen, ferrous iron may be soluble up to a few mg/l. Except on occasion at its surface, the mud at the bottom of lakes probably always has reducing properties and iron which has not been reduced in the water layers overlying the mud is reduced to the ferrous state. This ferrous iron will diffuse through the mud or be displaced by consolidation of the deposits and will eventually reach the aerobic zone.

"Upward transport may be promoted by the formation of methane or hydrogen sulfide in that portion of the deposits that is undergoing anaerobic decomposition. During stagnation periods, the iron content of the water overlaying the deposits will progressively increase. Ferrous iron which is transported through upward diffusion into the oxygenated waters near the surface will be oxidized to ferric hydroxide."

Figure 2 summarizes their thinking.

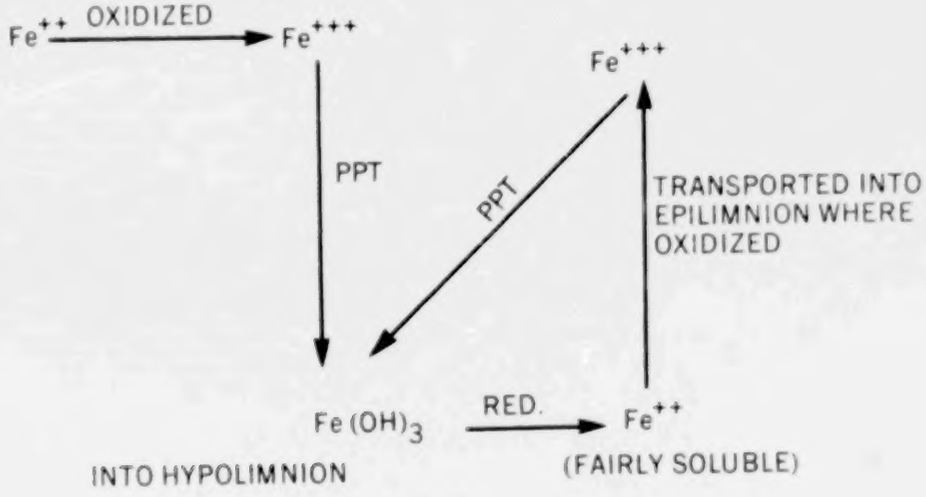

Figure 2. Summary of iron cycle, after Stumm and Lee (see Ref. 82).

Although microorganisms are responsible for the absence of oxygen in bottom waters and bottom deposits, the iron reactions mentioned by Stumm and Lee are all purely chemical. A paper by Morgan and Stumm,[83] "The Role of Multivalent Oxides in Limnological Transformations as Exemplified by Iron and Manganese," reiterates this cycle and adds important new information on the rates of oxidation of iron under differing environmental conditions.

Research Needs

Although some attention has been given to the iron cycle in impounded waters, further research is needed to delineate the effect of the environmental conditions in the overlaying water and in the bottom mud as they relate to the rate and extent of the dissolution of iron. Such factors as soil type, soil iron content, pH, alkalinity, chemical constituents of the overlaying water, oxidation-reduction potential, and bacterial content all undoubtedly have an influence on this dissolution. This influence must be evaluated.

Laboratory studies have been started by the Engineering Section at the Robert A. Taft Sanitary Engineering Center with the object of showing the influence of various environmental factors on the dissolution of iron. Initial studies will be made in soil-water contact

columns quite similar to those described by Sylvester and Carlson[84] in their report on the Howard H. Hanson Dam on the Green River in Washington, which was prepared for the Corps of Engineers.

MANGANESE

Existing Information

The manganese cycle in impoundments seems to have received much more attention in the literature than iron, possibly because of the greater difficulty in removing it during water treatment. Nine references starting in 1928 and proceeding to 1941 were concerned with maganese concentrations in and removal from bottom waters of deep impoundments. More recent work, however, by Ingols and his coworkers have sought to investigate the mechanism by which manganese is dissolved in impounded waters.

Recent attention has been given to the problem of high manganese concentrations in bottom waters by Churchill,[6] Love,[7] and Ingols.[67] Flentje[85] in an article entitled "How is Your Manganese?" states that manganese in storage impoundments is present in more areas than is suspected. He points out that impoundments in only nine states are probably immune from manganese and that approximately 0.1 percent of the earth's crust is manganese. The problems caused by manganese are reviewed by Myers[86] in "Manganese Deposits in Western Reservoirs and Distribution Systems." He notes that a reservoir may show a continual manganese concentration of less than 0.1 milligram per liter of water, yet the manganese can cause discoloration and lead to deposits in pipe lines and filter plants. He also remarks that the reaction of manganese and orthotolidine to give a color, and therefore a false chlorine residual, may seriously interfere with maintenance of safe water throughout a distribution system.

In their review "Mechanism of Manganese Solution in Quiescent Lake Waters," Ingols and Wilroy[87] suggest a mechanism of manganese solution in which trivalent manganese intracellularly accepts electrons and is reduced to soluble divalent manganese, which diffuses out of the cell. Ingols' current (1964) thinking, as reported in a private communication, is somewhat different, however.

Experimentation with *Pseudomonas fluorescens* showed that dissolution occurred when cell-free filtrates of a culture growing in the absence of manganese dioxide were added to a medium containing manganese dioxide crystals. All oxygen was removed from this medium by an actively growing *E. coli* culture, which was incapable of dissolving manganese. After 48 hours detectable quantities of soluable manganese indicated that the extracellular by-products of the *Ps. fluorescens* could reduce manganese dioxide. Figure 3 summarizes the dissolution.

The concepts of Morgan and Stumm[83] are shown in Figure 4. Their data indicate that a considerable quantity of manganous ion adsorbed to manganic or ferric oxide particles is carried into the

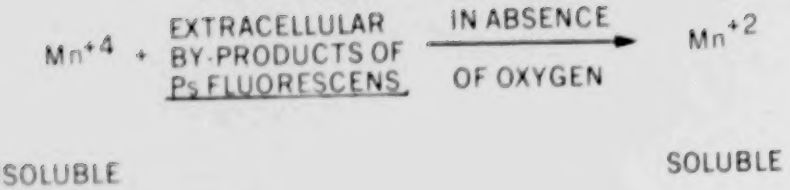

Figure 3. Manganese dissolution, after Ingols.

hypolimnion. This means that all of the manganese is not oxidized, even in the upper water where dissolved oxygen is present. Manganous ion is released into solution in the hypolimnion as a result of anaerobic bacterial activity in these waters. Morgan and Stumm agree in general with Ingols et al. that bacterial activity is involved in the manganese cycle.

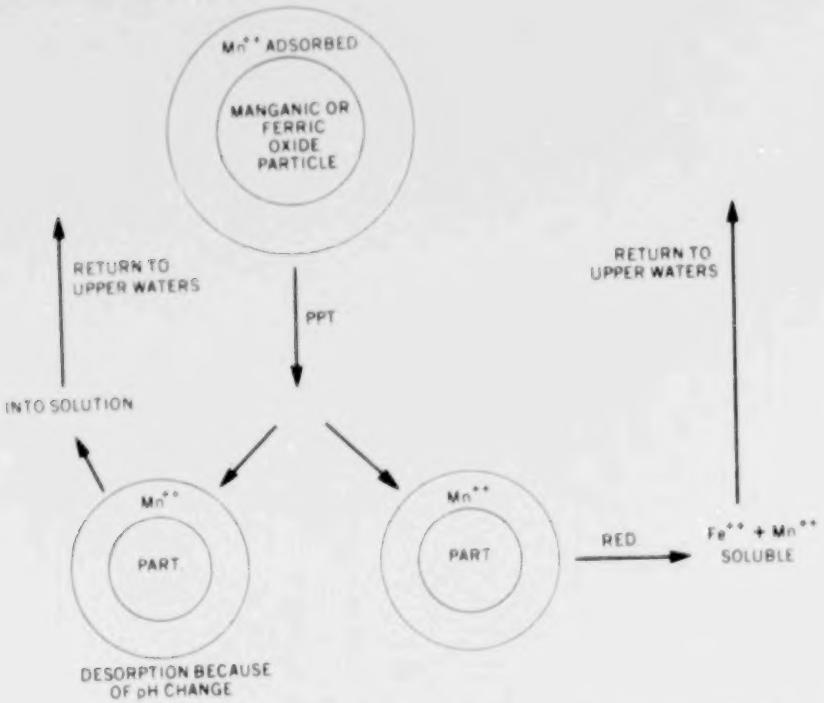

Figure 4. Summary of manganese cycle, after Morgan and Stumm (see Ref. 83).

Research Needs

Research needs related to manganese dissolution are similar to those mentioned in the iron section. Some additional study is needed to delinate the environmental factors that control the rate and extent of this dissolution.

Some attention to environment was given by Wilroy and Ingols[88] in "Aging of Waters of the Piedmont Plateau" in which they studied three impoundments in a single location near Newnan, Georgia. At the conclusion of this study these authors expressed the opinion that, "the manganese content of the bottom waters is a function of soil type."

Laboratory studies have been started by the Engineering Section at the Robert A. Taft Sanitary Engineering Center with the object of showing the influence of various environmental factors on the dissolution of manganese. Initial studies will be made in soil-water contact columns quite similar to those described by Sylvester and Carlson.[84]

NUTRIENTS

Existing Information

Any discussion of pollutional characteristics must recognize the pollutional potential of nutrient materials. Although nutrients are generally classed as pollutants because they support nuisance biological populations, sometimes they make water unfit for a specific use merely because of their presence. Many organisms, for example, slime-forming bacteria, aquatic weeds, rough-fish, and certain insects and insect larva can form nuisances, but the primary nuisance organisms stimulated by nutrient pollution are algae. The problem of increased algal productivity because of nutrient pollution was covered previously, and is not repeated in detail here. One excellent review of this subject, however, is "Algae and Metropolitan Wastes,"[22] the transactions of a seminar held on April 27-29, 1960, at the Robert A. Taft Sanitary Engineering Center.

In Committee Print No. 29 of the Select Committee on National Water Resources, United States Senate, which was prepared by Reid,[3] and titled "Methods of Approximating Dilution Water Requirements as a Supplemental Measure for Control of Water Quality in Rivers," three pollutional problems are discussed. The first relates to oxygen-demanding materials; the second deals with pollution from plant nutrients; and the third concerns pollution due to persistent chemicals. To quote from the Conclusions, "Three techniques for dealing with different kinds of water pollutants have been described. The limiting one in each instance should be the key to limits on future river developments. In general, the first, oxygen degradation, will become increasingly less important, as the degree of waste treatment increases, giving way to the second and perhaps eventually to the third." Therefore, Reid suggests that in the near future the major problem in river pollution will be caused by pollution from plant nutrients.

Research Needs

The research needs in this area have been discussed and are repeated here only in summary form. The prime research need in this area is to develop a fundamental understanding of the true nutrient requirement of some of the more common species of algae so that the relationship between eutrophication and the development of algae will be more clearly understood, or to develop a reliable operational test to determine the algae growing potential of a given water.

Organic Substances

OXIDATION AND PERSISTENCE OF ORGANICS

Existing Information

The organic content of impounded bodies of water has long been recognized. Hutchinson[18] in chapter 17 of his text and Derby[89] in his article "Chlorination of Deep Reservoirs for Taste and Odor Control" are two among several authors who have written about the subject. Derby's article notes that during thermal stratification of impoundments the creation of anaerobic bottom waters forms an environment in which taste- and odor-producing materials can result from decomposition of dead algae, weeds, leaves, and fish.

In spite of this attention to the organic content of impoundments, very little has been written specifically on the subject of the oxidation of organics in impounded waters. Hull[90] in his "Bibliography on Biochemical Oxygen Demand" has gathered together 314 references on this subject, covering the years 1927 through 1961. Although several of the articles were about oxidation of organic matter in the sea, the bulk of the articles concerned the BOD in flowing streams, only four references out of the 314 being directly applicable to impoundments. Ridenour,[91] who wrote "Studies on the Effect of a Small Impounding Reservoir on Stream Purification" found that in a small pond with a hydraulic detention time of about 3 days, calculations yielded a $k_1 = 0.168$ for deoxygenation and $k_2 = 0.26$ for reaeration. He felt that this indicated a more intense rate of deoxygenation and about the same rate of reoxygenation as could be expected in a flowing river.

Mohler[92] in his article "Assessment of the Self-Purifying Power of Surface Waters" discusses the results of observations over a 5-year period on the Aare River. He states that self-purification has been improved by reduction of the speed of flow and the increase in the surface area. He concludes by saying, "Creation of impoundments does not necessarily have an adverse effect on self-purification." ZoBell and Stradler[93] in "The Effect of Oxygen Tension on the Oxygen Consumption of Lake Bacteria" show that although the oxygen tension influences the multiplication of lake bacteria, their respiration is independent of the oxygen tension within the examined ranges of 0.3 to 36.5 milligrams per liter. Other useful articles in this general area are "Organic Pollution of New York Harbor — Theoretical Considerations" by O'Connor,[94] "Mechanisms of Self-Purification in Flowing Waters" by Jaag,[95] and "Investigations on the Influence of Retention by Dams on Natural Self-Purification" by Liebman.[96]

No direct consideration was found in the literature of the persistence of organic matter in impounded waters, but a potential problem was indicated in a paper entitled "Biodegradation of Surfactants Under Aerobic and Anaerobic Conditions" by Wayman, Robertson, and Hall.[97] In this article the authors note that under anaerobic conditions, synthetic detergents that are commonly accepted to be biodegradable aerobically were not decomposed. This same effect was noticed by Robeck and his coworkers who reported

that ABS was not metabolized in water-saturated soils,[98] but was metabolized in water-unsaturated soil columns.[99] Since anaerobic conditions may be present in the bottom of a deep, thermally stratified impoundment, synthetic organic chemicals, which may not cause a problem in aerobic waters because of their ability to be biodegraded, may persist in anaerobic bottom waters. A discharge of these waters, through power dams for example, might release a slug of this pollution to the downstream area.

Some organics are persistent or slowly degraded even in aerobic surface water, and the possible toxicity of these organics to aquatic life must not be overlooked. Extensive work on the toxicity of refinery effluents to fish life has been carried out by Irwin and his coworkers. An example of his work is contained in the article "Evaluation and Relative Resistance of Sixteen Species of Fish as Test Animals in Toxicity Bioassays of Petroleum Refinery Effluents" by Douglas and Irwin.[100] A valuable bibliography also appears with this article.

Research Needs

The rate of oxidation of organic matter in impounded waters, and the possibility of the persistence of organic materials that are ordinarily biologically decomposable must be further evaluated. Organic pollution is likely to exist in most impoundments, and its behavior must be understood if the overall behavior of the impoundment with respect to water quality is to be known. Some laboratory and field work with such devices as the new total organic carbon analyzer developed by the Dow Chemical Co. may help to understand the true rates of oxidation of organic matter in impounded waters.

A 500-gallon, 3-foot-diameter, 10-foot-deep pilot plant has been developed by the Engineering Section at the Robert A. Taft Sanitary Engineering Center for the artificial creation of thermal stratification in a water column. In this apparatus laboratory studies have been started on the rates of oxidation or persistence of artifically induced contaminants, or both in thermally stratified water. This laboratory apparatus, as well as the previously mentioned field studies, should provide useful information in an area where further research is badly needed.

METHANE

Existing Information

The formation of methane in the bottom muds of marshes and swamps has been recognized for many years. In spite of this, however, very little attention has been given in the literature to evaluating the true meaning of this mechanism in the overall carbon cycle in standing bodies of water. This is unfortunate, since methane fermentation is an important mechanism by which carbon is truly lost from an impoundment environment.

Algae give off oxygen while converting carbon dioxide, an inorganic carbon source, into new cellular protoplasm which is organic carbon. Bacteria use the evolved oxygen to metabolize organic matter, and in so doing produce carbon dioxide. Therefore, bacteria change organic carbon into inorganic carbon. If no oxygen is added from an outside source, and no carbon dioxide is lost to the atmosphere, this cycle is unbreakable, and no true removal of carbon occurs, although as Hull[46] points out, the relative rates of these reactions are important. If, however, the algae or the bacteria in the above mentioned cycles settle into the bottom muds and undergo methane fermentation, and the methane escapes, carbon will be truly lost from the cycle.

One recent attempt to evaluate methane production in waste stabilization ponds was reported by Oswald, Golueke, Cooper, Gee, and Bronson[101] in their article, "Water Reclamation, Algal Production, and Methane Production in Waste Ponds." The rate of methane production was measured in the bottom muds of 4- and 7-foot-deep waste stabilization ponds. Under optimum conditions 8 to 10 cubic feet of gas per pound of volatile solids applied could be obtained; this figure is roughly equivalent to the gas production for anaerobic digestion of sewage sludge. The gas contained a high percentage of methane, but, surprisingly, contained very little carbon dioxide. The main problem discovered was one of temperature. Methane fermentation is very temperature-sensitive; and in ponds in which the temperature did not exceed 14°C, the rate of methane fermentation was low. Since sewage sludge digestors are commonly heated to 35°C to obtain rapid rates of methane production, methane fermentation would be expected to be slow in cold water. This dependence on temperature is particularly pertinent to the conditions in stratified impoundments.

Research Needs

The research mentioned above was done in oxidation ponds, and therefore may not be strictly applicable to deep impoundments. Measurements of the rate and extent of methane fermentation must be made in the hypolimnion waters of deep impoundments. As mentioned by Oswald, et al.,[101] under low-temperature conditions, the rate of methane fermentation is slow. Because of the extremely long water detention time in large impoundments, this slow rate may still allow for a significant quantity of methane production. In a large impoundment, methane fermentation could be an important mechanism in the carbon cycle, even in cooler waters. The validity of this statement must be checked with further laboratory and field investigations on methane fermentation.

Currently (1964) Brezonik is carrying on Doctoral Research under the direction of Lee, at the University of Wisconsin, on the concentration and distribution of oxygen, nitrogen, methane, and carbon dioxide in lake waters. These gases will be trapped and analyzed by gas chromatographic techniques. Results of this study should be quite valuable.

COLOR

Existing Information

Major work is currently (1964) being done on the nature of natural color by Shapiro at The Johns Hopkins University and Black at the University of Florida. The work by Shapiro seems the more pertinent for the purposes of this paper. In 1960 Shapiro[102] prepared a project proposal that led directly to the Research and Training Grants Branch Project "Inorganic - Organic Interactions in Natural Waters," Grant Number WP-00199. This project started in 1961 and is continuing. The following quotation from Shapiro's unpublished project proposal is included with the author's permission:

> "The importance of the dissolved organic matter as a part of the aquatic environment is becoming more and more apparent. Not only is the dissolved organic matter quantitatively important (being up to 20 times the suspended organic matter, including organisms), but it must play a significant role in the environment, for limnologists and oceanographers are realizing that a knowledge of only the inorganic constitutents of water cannot fully explain the phenomena observed. Therefore, it is essential that this hitherto neglected factor be given some attention.
>
> "One fraction of the 'dissolved organic matter' which, because it is so readily apparent, has long generated speculation, is the yellow coloring matter of 'humic' matter which is found in all natural (fresh) water.
>
> "Work by the principal investigator over the past nine years has led to the elaboration of techniques for the safe and large-scale recovery of these substances and has elucidated many aspects of their nature, role and distribution. It is proposed that this work be continued in hope of ultimately providing answers to the many unanswered questions of fresh water biology and chemistry.
>
> **"Specific Aims**
>
> The following aspects will be included in the study which will be restricted almost exclusively to fresh water.
>
> 1. Physical state of the coloring matter.
> 2. Chemical nature of the coloring matter.
> 3. Relationships between color and the inorganic constituents of the water.
> 4. Significance of the above, especially Number 3, to the plankton organisms.
> 5. Comparison of waters from different parts of the world."

The epilimnion may be 5 to 50 feet deep depending on impoundment depth and other factors. The impoundment is mixed to this depth by wind-induced currents, and this layer has a uniform temperature. Below the epilimnion is the thermocline, which may be 5 to 20 feet deep. The thermocline is a stratum in which the temperature decreases rapidly as depth increases. A thermocline has been defined for convenience, though on a strictly arbitrary basis, as a stratum of water in which the temperature decreases 1°C or more in the depth of 1 meter, or 0.55°F per foot. The decrease in temperature is accompanied by an increase in density, with a corresponding increase in resistance to mixing. In the hypolimnion the water is protected from the atmosphere by the overlying thermocline and epilimnion; therefore, very little increase in temperature occurs after stratification is established. Temperatures are low and quite uniform throughout the hypolimnion.

Summer stratification persists until the fall when the influent water becomes cooler. The cooler water is mixed throughout the epilimnion and the upper portions of the thermocline by convection and wind action. Cooling continues until the temperatures and densities of the epilimnion and thermocline approach those of the hypolimnion. When this is accomplished, resistance to mixing is diminished, and the fall overturn occurs.

In northern climates, winter stratification can occur because 0°C water is lighter than 4°C water. This density difference can produce thermal stratification, although now the colder water is the top water. The prevention of wind mixing because of ice cover maintains this stratification, if such a cover exists.

As reported by Kittrell,[105] the difference in density per °C is much greater at higher temperatures than it is at lower temperatures. As shown in Figure 5, the difference in density between 25° and 30°C water (1.40 mg/ml) is 2.34 times larger than the difference in density between 10° and 15 °C water (0.6 mg/ml). This means that even if an impoundment showed a rather modest temperature gradient that never reaches the intensity of a thermocline, it could still be density stratified. Generally warmer waters stratify with a smaller temperature difference than colder waters. This factor is specifically discussed by Marlier[105] in his article "The Biology of Tropical Lakes," in which he notes extreme stability in lakes having a water temperature near 25°C.

Research Needs

Although the thermal cause and the chemical effect of thermal stratification have been adequately studied and reported, the effect of physical factors and the environment on the presence or absence of thermal stratification has received little attention.

Previous research has not enumerated which environmental factors tend to enhance or inhibit thermal stratification. This situation must be remedied if the site of a planned impoundment is to be evaluated on the basis of its thermal stratification potential. In studies under way

tion of impoundment, (13) inflow pattern, and (14) weather during the period of the onset of stratification. The correlation of these factors through the use of a discriminate function, to the presence or absence of thermal stratification in existing impoundments will reveal which factors have the major influence on thermal stratification.

DENSITY FLOWS

Existing Information

Density flows, which are defined as streams of water that flow under, over, or through water of slightly different density, have long been recognized in stratified impoundments. The earliest detailed reference found was Wiebe[106] who discussed these in 1939 in his paper entitled "Density Currents in Norris Reservoir." He refers, however, to work done by Monish and Keulegan in 1930, and so density currents were being studied at least that long ago.

In a thermally stratified impoundment with light water on the top, heavy water on the bottom, and intermediate density water in the thermocline area, an influent of a given temperature either flows across the bottom if it is cold, across the top if it is warm, or through some intermediate zone if it is intermediate in temperature. These flows are named underflow, overflow, or interflow, respectively.

Density flows have been used to prevent siltation by discharging silt-laden water through an opening at some specified level in a dam face. The power industry has also made use of density flows by choosing an appropriate level from which to draw cooling water, thereby maintaining the flow of a certain temperature water into their steam-generating plants.

The density currents in Lake Mead, caused by sediment load, not temperature differences, have received attention because of the siltation of the lake. An extensive survey of Lake Mead was begun in January 1948 and completed in late 1950. This was carried out jointly by the Geological Survey, the Bureau of Reclamation, and the Bureau of Ships of the Department of the Navy. The three-volume report published jointly in 1954[107] and the condensed version published by the Geological Survey[108] are worthy of review, not only because of the interesting analysis of the density currents, but also because of the intense discussion of the physical, chemical, and biological changes caused by the formation of Lake Mead.

The Task Committee on Preparation of a Sedimentation Manual of the Committee on Sedimentation of the Hydraulics Division of the American Society of Civil Engineers is publishing portions of the proposed manual in the *Journal of the Hydraulics Division.* The portion "L. Density Currents"[109] is a very useful review of the subject and contains a good bibliography.

Churchill of TVA reported in a private communication that in the fall season, cooler inflows to Cherokee Reservoir passed through the power intakes in about 2.5 weeks when the theoretical hydraulic

GPO 823-506-4

detention time of the reservoir, V/Q, was much longer. This type of underflow, or interflow, can be quite striking. A turbid influent can be seen flowing a certain distance into an impounded body of water and then disappearing. The plunge point - where the water, seeking a zone with the same density, dips down into the bulk of the liquid - is often so sharp that a fairly straight line of floating debris accumulates across the surface of the reservoir along the line at which the influent water begins to submerge.

Research Needs

One current piece of research on this problem is being carried on at the California Institute of Technology with support of the Research and Training Grants Branch of the U.S. Public Health Service's Project WP-00248. The title of this project is "Dynamics of Density-Stratified Reservoirs." In spite of the knowledge of the existence of density currents for many years, and the current research being done in this area, further research is needed. This need can best be summarized by quoting from a report entitled "Internal Density Currents Created by Withdrawal from a Stratified Reservoir,"[110] a cooperative study of the Tennessee Valley Authority and the U.S. Corps of Engineers. They state:

> "The need for knowledge of the character of internal density currents in reservoirs has become increasingly important in recent years because of the intensified multi-purpose use of such projects. Some of the uses of many reservoirs can only be optimized by knowledge of, and in some instances control of, internal currents. A few examples of the problems involved are: need to maintain cool, potable, domestic water; need for the coolest water possible for cooling thermal-electric power generation plants; need for maintaining water quality suitable for recreation, and for fish and wildlife; and need for manipulating water supplies to retard undesirable aquatic growth.
>
> "Internal density currents have been studied by theoretical approaches, laboratory experiments, and direct measurement of velocities and stratification in prototype reservoirs. However, no clear-cut procedures have been made available for estimating in advance the internal density currents that might be expected in a proposed reservoir or for determining how such currents might be controlled. Reliable field data on velocities, temperature and density variations in deep reservoirs, are very meager. In addition, most of the theoretical studies and laboratory experiments have been only vaguely applicable to reservoirs in which densities often vary quite gradually with depth."

Perhaps the sensitive Savonius Rotor current meter (measures to 0.017 ft/sec) or the Deep Water Isotopic Current Analyzer (range

0.0034 to 17 ft/sec) developed by the William H. Johnston Laboratory of Baltimore, Maryland, will prove useful in density current studies.

ARTIFICAL DESTRATIFICATION OF IMPOUNDMENTS

Existing Information

Natural mixing and wind-induced currents have been studied in impoundments. Likens and Hasler [111] in "Movement of Radiosodium in a Chemically Stratified Lake" used sodium-24 to demonstrate horizontal movement of about 16 to 18 meters per day in all directions, but found no vertical movement. Lathbury, Bryson, and Lettau [112] in "Some Observations of Currents in the Hypolimnion of Lake Mendota" showed that hypolimnion currents are very slow and are caused by a redistribution of density by the wind. Although currents do exist, they are too feeble to cause aerated water to penetrate into the hypolimnion and prevent the deterioration of water quality there. If destratification is to be accomplished, it must be done artifically.

The concept of mixing large bodies of water is not new; the first attempt was reported in 1952 by Hooper and Ball [113] in their article entitled "An Experiment in the Artificial Circulation of a Small Michigan Lake." In the years between then and now (1964), at least 18 attempts (one on a model basis) have been made. Most of these have caused an improvement in the water quality of the impoundment or lake. Several different methods have been used, under different conditions and for different periods of time, but two features seem to stand out: (1) in a short time after the start of the operation, the degree of stratification was markedly reduced or eliminated, in most of the cases and (2) the amount of equipment required was modest, considering the volume of water mixed.

Most authorities agree that the prevention of the deterioration of the hypolimnion through impoundment destratification would be beneficial. Mixing would prevent: (1) low dissolved oxygen concentrations, (2) increased iron and manganese concentrations, (3) production of hydrogen sulfide, and (4) increase in color, in the hypolimnion. Mixing would, however, prevent the accumulation of cool waters in the impoundment bottom and might increase overall productivity of the lake by recycling back into the euphotic zone nutrients released during organism decomposition.

Relatively small bodies of water have been mixed in the past, the largest reported in the literature being near 13 billion gallons (about 40,000 acre-ft). Derby [89] in 1953 reported on mixing the 13.2-billion-gallon lower Hollywood Reservoir with a diffused aeration system. He noted that this aeration lowered the thermocline, but did not completely prevent stratification. In 1954 Mercier and Gay [114] reported on the mixing on Lac de Bret, with a capacity of 13.1 billion gallons, by pumping from the bottom water and discharging the pumped water at a depth of 45 feet, 600 feet away from the pump.

They noted that this mixing kept the lake 97 percent saturated with oxygen during one summer. Bryan[115] in his article "Improvement in the Quality of Reservoir Discharges Through Reservoir Mixing and Aeration" reported on the mixing of Inniscarra Reservoir, which has a volume of 12.5 billion gallons, through the use of Aero-Hydraulic Corp. patented equipment, a large water pump with an air piston. The dissolved oxygen concentration only fell from 9 milligrams per liter in May, when the mixing started, to 3.5 milligrams per liter in July during 1961, while it fell to zero over the same period the previous year. This happened even though the rated pumping capacity of the equipment was only 20 million gallons per day. As was hoped, extra water was entrained during operation of the equipment.

While some attempts at mixing were more successful than others, only one experiment of the 18 described in the literature was not successful. Patriarche[116] in an article entitled "Air-Induced Winter Circulation of Two Shallow Michigan Lakes" tried to mix two shallow lakes with compressed air pumped in through a perforated rubber hose. He found this treatment ineffective in preventing depletion of dissolved oxygen, and the temperatures of both the water and the bottom muds were lowered. Since this technique has been quite successful in other lakes, the cause of these problems is not known. In this case fish mortalities occurred, and Patriarche felt that the air-induced circulation helped to cause these deaths instead of preventing them.

Research Needs

The research needs in this area fall into three catagories: (1) to determine whether artificial circulation of larger storage impoundments is technologically feasible; (2) if this is possible, to determine the most economical means and cost of circulation; and (3) to determine the total effect of circulation on the water quality in an impoundment.

Wherever the field investigation is done, it must encompass a comparison of the two or three major methods of moving large quantities of water through a low head. These methods must be compared on the basis of economics, as well as performance. While the tests are being made, sufficient measurements must be taken to evaluate the total effects on the water quality, both beneficial and adverse. Finally, such factors as the best time to start mixing and the duration of water movement after deactivation of the power source must be evaluated. To obtain some preliminary information on artificial destratification, the Engineering Section at the Robert A. Taft Sanitary Engineering Center has assembled a 3,500-gpm, raft-mounted low-head pump for drawing cold bottom water to the surface where it is discharged. Initially this equipment will be tried on small, 30-million-gallon lakes. If this operation is initially successful, destratification will be attempted in a larger lake of 0.5 billion gallons. Mixing of large volumes of water may be impractical or

detrimental, or it may be a very worthwhile solution to many of the present problems in impoundments. Only research will settle the issue.

EVAPORATION CONTROL

Existing Information

Most of this report deals with water quality characteristics and criteria, but streamflow regulation may also be undertaken to help meet a downstream water quantity criteria. As Neel has pointed out in an unpublished report, whenever an impoundment is constructed to regulate streamflow, the flow variation in the stream may be smoothed out, but the total annual flow will be reduced, except in humid areas, because of increased evaporation from the impoundment. Since this is the case, and downstream water quantities are important, the possibility of reducing evaporation becomes an important consideration. One estimate by Meyers[117] in "Evaporation from the Seventeen Western States" gives the annual loss from impoundments in these western states at 15,600,000 acre-feet per year, but the Senate Select Committee sets the loss at 21,000,000 acre-feet per year. Recently an American Water Works Association group, Task Group 2480R- Evaporation Control, with Curtis Michel as chairman, reported on "Survey of Methods for Evaporation Control".[118] This is a very useful review of the entire subject of evaporation control and contains 54 references.

This group suggests seven important considerations in the field of evaporation control:

1. Siting - "Of all the methods that have been suggested to control evaporation from reservoirs, site location is perhaps most important. If a reservoir can be situated to reduce the effects of shallow areas, high winds, and perhaps even excessive solar radiation, evaporation losses can be reduced.

2. Shallows - "Avoiding extensive areas having shallow water depth should help to curtail excess evaporation losses. The costs of the fill or diking and maintenance would have to be considered for each situation. . . . Areas shallower than the depth of annual evaporation contribute little to useful storage and may serve to increase salinity.

3. Phreatophytes - "Non-beneficial, water-consuming plants, phraetophytes, are generally regarded as a nuisance. These will be found mostly in the shallows and along the shoreline. But before they are removed, the possibility of increased erosion should be considered as well as whether the costs of removal and possible hazards to aquatic life and ecological balance of the reservoir or lake are justified by the savings.

(The Senate Select Committee[3] estimates a yearly loss of 22,000,000 acre-feet by phreatophytes in 17 western states.)

4. Wind breaks - "Similarly, wind breaks must be considered in the light of their net contributions to water savings. Obviously trees and plants consume water . . . One report states that tree planting along lake shores can reduce winds to leeward up to a distance of 20 times their height. Whether the reduction in evaporation that a somewhat reduced wind force will effect is greater than the water requirements of the planting is not clear.

5. Covers - "Floating covers, consisting of reflective material such as white polyethylene spheres, have been used on oil storage tanks and tested on water storage. Cost and interference with other reservoir uses limit this method, while capillary action is liable to render it ineffective under slight wave action. Solid plastic covers are similarly impractical for large storages and interfere with gaseous exchange. Roofing reservoirs has been suggested and the costs have been estimated. The costs appear excessive and the installation would conflict with the various uses to which reservoirs are put, in particular with the role as fish and wildlife preserves and with the increasing recreational use.

6. Seepage - "Seepage, while not properly within the discussion, is a reservoir water loss that should be mentioned. On large water storages, reduction of seepage by treatment with soil stabilizers probably costs more than the value of the water that may be saved, though this appears to be a feasible method for ponds and canals . . . As an impoundment ages, seepage losses are reduced.

7. Monolayers - "It may be inferred from the discussion that there are two ways to reduce evaporation: (1) Decrease the surface area of the water exposed to the air, or (2) lessen the effects of the physical forces that cause evaporation. The method of controlling evaporation by the application of a monomolecular film may be regarded as doing both, by damping the microwaves and imposing an additional physical resistance."

In this article, and in research through the years, the greatest attention has been given to the possibility of evaporation control by covering large impoundments with monomolecular films, using either normal hexadecanol or normal octadecanol to suppress evaporation. Under ideal conditions, these films are remarkedly effective in retarding evaporation. But in a field situation because of such

adverse conditions as wind, waves, bacterial degradation, molecular holes arising from incomplete evaporation of solvents, entrapped foreign materials such as dust, and inability under certain conditions to maintain film compression, the effectiveness of this treatment has been reduced. Most of the field trials have shown very modest results, although the Task Group admits that it is very difficult to truly measure the effect of these films in a field situation. Another very useful reference on this subject is a collection of 19 papers presented at a symposium on September 15, 1960, titled "Retardation of Evaporation by Monolayers," The work is edited by Professor Victor K. LaMer.[119]

Research Needs

Investigations in this area have been both promising and disappointing. Control of this enormous water loss is too important to neglect, however. Therefore, research efforts refining the hexadecanol method and seeking an entirely new approach should continue. An unpublished internal Basic and Applied Sciences Branch document contained the following note from the Microbiology Section at the Robert A. Taft Sanitary Engineering Center. "New data indicated that complexing iodine and various fatty alcohols may prolong the film life of monolayers. An instrument has also been developed which allows accurate, rapid determination of the evaporation suppression efficiency of monolayers along with the film pressure. These developments will markedly aid in the final solution of the usefulness of monolayers in evaporation suppression." It is also of interest to note that only one Research Grants Branch project on this subject, "Evaporation Suppression and Its Effects on Biota," Grant Number WP-00160, supervised by Franzini, could be found in their 1963 List of Awards.

THERMAL POLLUTION

Existing Information

The addition of warm water to an impoundment, either because of the warming of the influent waters because of solar radiation or because of the discharge of warmed cooling water from industrial processes, influences the water quality in impoundments. These warm waters tend to stay near the surface of the impoundment. This warm water influences aquatic life in the surface waters of the impoundment, influences the rate of deoxygenation from biological degradation of organic matter by speeding the process, and influences dissolved oxygen concentrations because of decreased solubility of oxygen in higher temperature water. The latter reduces the surface deficit, and thereby reduces the reaeration rate.

Thermal pollution of streams has received some attention in the literature. Hoak [120] in "The Thermal Pollution Problem," Arnold[121] in "Thermal Pollution of Surface Supplies," and Churchill [122] in "Control of Temperature Through Streamflow Regulation" are

some of the authors who have given attention to this problem. The first two articles discuss problems of the danger to aquatic life and of lowered dissolved concentrations caused by warmer wate . In addition they suggest criteria for avoiding problems. Hoak[120] refers to the work of the Pennsylvania Sanitary Water Board and quotes the regulations for the Commonwealth on stream water temperature. Duttweiler[123] in "A Mathematical Model of Stream Temperature" has developed a model, which works reasonably well in a small stream and can be used to predict downstream temperatures below a streamflow regulation release.

Churchill's article is more concerned with the influence of discharging colder hypolimnion water on downstream water temperatures. He shows that the water temperature can drop abruptly from a river water temperature of 75°F down to the hypolimnion temperature of 45°F when large discharges of hypolimnetic water are made from an impoundment. This large a temperature change places considerable stress on downstream aquatic life.

One article found discusses in detail thermal pollution in impoundments; Eckel[124] in "Temperature Condition in Impounded Waters" discusses conditions of uptake, distribution, and discharge of heat in flowing and impounded waters and the differences between natural lakes and impounding reservoirs. These differences are illustrated in this German article by records of measurements in a large number of lakes and impounding reservoirs.

The Proceedings of the Twelfth Pacific Northwest Symposium on Water Pollution[125] Research entitled *Water Temperature, Influences, Effects, and Control* is an important review of this thermal pollution problem, as is indicated by some of the papers included, which are listed below:

1. "Temperature as a Water Quality Parameter" C.M. Everts.
2. "Effects of Water Uses and Impoundments on Water Temperature" by R.O. Sylvester.
3. "Temperature Phenomena and Control in Reservoirs" by J.M. Raphael.
4. "Some Observations of Columbia River and Reservoir Behavior from Hanford Experience" by R.T. Jaske.
5. "Instrumentation for Water-Temperature Studies" by A.M. Moore.
6. "Summary of Current Theories and Studies Relating to Temperature Prediction" by R. Zellar.

Jaske agrees with Churchill[122] that water control structures can have a profound influence on temperature and, if designed and used properly, can promote desirable downstream conditions while avoiding undesirable ones. This reemphasizes the need to understand the influences caused by the design and operation of outlet works.

Research Needs

While the problem of thermal pollution in streams has been investigated and discussed in the literature, little information concerning these same effects in impoundments has been published. Addition of warmed water to an impoundment may well affect its behavior, and this effect must be understood to gain complete understanding of impoundments. These studies should be on a field scale since studying this problem on a laboratory scale would be difficult. A large, well-instrumented model impoundment containing typical aquatic life might be used, however, to gain some insight into the influence of the introduction of heated waters. The blending of warm and cool waters is a problem in mixing, and the references noted in the section on Turbulent Diffusion and Natural Mixing may be applicable here.

Summary of Russian Experiences

Reference is made to a Russian article, "Prognosis of Reservoir Quality," by Chibov.[126] This article is of particular interest since it summarizes the state of knowledge of reservoir behavior as understood by Russian investigators. A review of various abstracting journals has revealed that there is a great deal of interest in Russia, Czechoslovakia, and Yugoslavia on the general topic of water quality behavior in impoundments.

In Chibov's article an equation is given for the calculation of the changes in mineral content of an impoundment between seasons T and seasons T + 1. The author is enthusiastic about the formula, which takes the form of a mineral balance in a given impoundment, but is critical of the fact that the studies on which the formula was based were all made in impoundments near one geographical location. He also points out that merely being able to forecast mineral content does not truly give a complete picture of the effects of reservoirs on water quality. He suggests that physical, chemical, bacteriological, and other biochemical aspects of water quality must all be understood in an impoundment environment. The author is also critical of members of the VODGEO Research Institute, who developed the previously mentioned prediction formula, in the following statement. "In the first, they make no reference to river basin classifications; they disregard the effects of local conditions, such as river slope, shape of bed in either sectional direction, size of the flooded area above and to either side of the dam, the rate of water flow, direction of prevailing winds, etc. Their approach to the problem is of an abstract character and has no direct bearing on concrete cases."

From this quotation and the tone of the remainder of the article, it would appear that although intensive studies have already been made in the USSR, additional work is needed in order to develop a complete scheme that will allow the understanding of the influences of impoundments on water quality. This thought is echoed in a conclusion in the U.S. Public Health Service's report on the "Pearl River Shallow Water Reservoir Water Quality - Recreation Project"[35] which states, "while some water quality changes such as turbidity and bacterial reduction and temperature stabilization may be expected to result from impoundment, it is difficult at this time to make further predictions, i.e. algal growth potential, manganese content increase, etc."

The Tennessee Valley Authority has made several studies on this problem through the years. Churchill, in a talk entitled "The Effects of Reservoirs on the Water Quality," presented at the National Council for Stream Improvement's Annual Meeting, February 18-21, 1963, discussed one situation in which extremely high manganese concentrations developed in the bottom waters of an impoundment. He noted that these concentrations were so detrimental to downstream water quality that bottom water could not be drawn from this reservoir. In the paper mentioned previously, Churchill[122] discusses the influence of withdrawals from deep impoundments on downstream water temperature.

Pfitzer[127] discusses the influence of impoundment discharge on fish populations in an article entitled "Investigation of Waters Below Storage Reservoirs in Tennessee." He states:

> "These various chemical and physical changes have caused radical alterations in the plant and animal life. Two very striking examples show the effect on the fish populations. An unpublished preimpoundment survey in 1947 by Charles J. Chance and Reeve M. Bailey in the South Fork of the Holston and Watauga Rivers recorded 43 species for South Fork and 32 species for Watauga. After construction of the dam and subsequent discharge of cold water, only 17 species of fish have been recorded for South Holston tailwater and 13 for Wautauga and Wilbur tailwaters on the Wautauga River."

Research Needs

The literature cited above is concerned with the detrimental effect on water quality because of the discharge of poor quality water from impoundments. No discussions were found concerning the beneficial effect that might accrue from the discharge of good quality water. Yet, this is precisely the goal of a streamflow regulation project, the discharge of high-quality dilution water that will have a beneficial effect downstream. One might presume that if the dilution water were of good quality, the effect on a given water quality characteristic downstream could be calculated on a weighted proportion basis, taking into account the relative concentrations of the substance under consideration and the relative volumes of the downstream water and the dilution water. For substances that do not undergo reactions, such as chlorides, this approach is probably valid, but it will not necessarily work for all substances.

Several effects need to be investigated. Examples of these are as follows:

1. The influence of dilution on rate of biological deoxygenation must be investigated. The dilution of a given polluted stream may cause an increase or a decrease in the rate of biological oxidation of the organic matter in that stream.
2. Because of increased turbulence and increased depth caused

by increased flow, the rate of reaeration may be changed in a given situation when dilution water is added.

3. Because of increased flow, the time of travel between a source of pollution and a possible water use will be shortened. In certain situations poorer quality water may arrive at a downstream point because this decreased time of travel would decrease the opportunity for natural purification to occur.
4. If algal toxins are present in the river, and these toxins are preventing an undesirable bloom of algae, the dilution of this water with toxin-free water from an impoundment may well result in undesirable effects.
5. The discharge of good chemical quality, but low-temperature water, may interfere with downstream recreational facilities, or the type of fish present.
6. The absence of fish life below some dams discharging hypolimnion water, even though it has been reaerated, has lead to the supposition that in the reducing environment of the hypolimnion, substances toxic to aquatic life are produced. If this possibility is true, it must be investigated since even on reaeration, this water may be undesirable as dilution water.

These six topics are areas in which additional information is needed badly if the complete effect of a streamflow regulation scheme is to be assessed. Many of these studies can be carried out in the laboratory by blending various concentrations of river water with dilution water of a given quality and the resulting behavior of the mixed waters determined. Extreme care must be taken when making stream studies under laboratory conditions, however, because a field situation is so much more complex and probably never can be actually duplicated in the laboratory. Other problems, such as the influence of decreased time of travel, may better be studied in a controlled field situation. In summary, the influence of impoundment releases on downstream water quality is a challenging but potentially fruitful and necessary area for continued investigations.

TURBULENT DIFFUSION AND NATURAL MIXING

Existing Information

An adequate knowledge of mixing phenomena in rivers is essential to assure the most efficient use of dilution water. If dilution water becomes channeled and does not mix with the entire contents of a river, the entire benefit of this water will not be realized. This problem would be accentuated in wide, relatively slow moving rivers where waste inputs as well as dilution water might cling to one shore or the other and might be very slowly blended. Wisniewski[130] in "Cross-Section Surveys as a Method of Evaluating the Self-Purification Capacity of a Stream" reports on a situation in which an effluent remained on the same side of a river as the original discharge for 12.5 miles downstream.

The mathematical models needed to describe turbulent diffusion are complex and only recently have been attempted by various investigators, previous studies being made with the help of tracers as described by Thomas and Archibald[131] in "Longitudinal Mixing Measured by Radioactive Tracers." Currently, important research on this problem is being carried out at Vanderbilt University under the direction of Krenkel. As the title of his U. S. Public Health Service project, WP-00328, Turbulent Diffusion and River Waste Assimilative Capacity, indicates, he is interested in turbulent diffusion as it influences reaeration (Krenkel and Orlob[60]), but his research will also give valuable insight into mixing phenomena.

To review this subject, portions of Krenkel's Project Progress Report[132] are quoted below.

"(1) Eddy Diffusion

Oceanographers and meteorologists have long used the analogy between diffusion of matter on a microscopic scale and the spread of a tracer material on a macroscopic scale to describe turbulent mixing in the ocean and in the atmosphere. This process can be described by Fick's second law, which is

$$\frac{\partial C}{\partial t} = D_E \frac{\partial^2 C}{\partial x^2} \qquad (2)$$

in which C is the concentration, t is the time, x is the distance, and D is the eddy diffusion coefficient. Although the analogy has been subjected to question, one can find much experimental evidence of the molecular diffusion process on a macro-scale as applied to the spread of tracers in a turbulent field both in the ocean and in the atmosphere. An excellent summary of the process, including experimental verification of the analogy, can be found in a report by Harlemann et al. (1).

Although equation 2 has been used successfully in numerous diffusion investigations, it should be recognized that in the case in question, (that is, in open channel flow), use of this mathematical model may result in erroneous conclusions. The concentration gradient predicted by this model may be in error because of the neglected mass transport caused by the convective velocity. Also, the eddy diffusion coefficient as previously defined describes mixing at a point in the flow, and as such may not be the parameter desired to denote mass transfer in a stream section. To predict the mixing characteristics of a river section using equation 2, it would be necessary to determine the eddy diffusion coefficient at numerous points and then use an appropriate averaging technique to obtain the overall description of mixing in the section under consideration. As shown subsequently, this averaging process is performed auto-

matically when the longitudinal mixing coefficient is used.

(2) Longitudinal Mixing Coefficient

Consider an experiment in which an instantaneous dose of tracer has been injected into an open channel where the water is flowing at a mean velocity, $\bar{u}$. If samples are taken with respect to time at a station downstream from the point of injection, the flow pattern will typically follow equation 1:

$$\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} - \bar{u} \frac{\partial C}{\partial x} \qquad (1)$$

which is the general differential equation describing the mixing process of the injected tracer. A solution of this equation is

$$C = \frac{M}{A(4\pi D_L t)^{1/2}} \exp\left[- \frac{(x - \bar{u}t)^2}{4D_L t} \right] \qquad (3)$$

where M is the weight of injected tracer material, A is the cross sectional area and x is the distance downstream from the point of injection.

Equation 3 has been found to describe very closely the temporal distribution of an instantaneously injected tracer, and is similar to the equation developed by Taylor (2) (3), partly by intuition. Examination of this equation shows it to be representative of the normal error curve if the tracer distribution with distance is observed at a particular time. Normally, in experiments of the type described, the tracer is instantaneously injected and the concentration distribution as a function of time is observed at a fixed station downstream. Obviously, because the exponential denominator in equation 3 is no longer constant in this case, one would expect to obtain a skewed time-concentration distribution. This observation has been made by Taylor who states that the asymmetry should be negligible when the observation point is greater than 100 pipe diameters downstream from the point of tracer injection. A physical explanation of the skewness may lie in the fact that diffusion is taking place while the tracer cloud is passing the observation point.

It should be noted that when a significant laminar sublayer exists, the time-concentration curve may not follow equation 3 because of the slow release of tracer particles from the sublayer itself. This could explain the extremely long tails that are obtained in tracer tests conducted in sedimentation basins, for in this case it is

highly probable that a significant laminar sublayer is present.

Elder (4), in an attempt to explain the deviation of the observed time-concentration curve that is sometimes obtained from the theoretically predicted distribution, proposed the following mechanism. The observed time-concentration curve is considered to be composed of two components — the primary one corresponding to tracer that is carried in the turbulent flow regime, and the secondary one resulting from the slow release of tracer existing in the viscous sublayer. Elder considered that particles contained in the laminar layer could only be released to the turbulent portion of the stream via the process of molecular diffusion."

Note, the references are for those contained in the original report. A useful bibliography containing 20 references on turbulent diffusion is included in this report.

Krenkel concludes his literature review on mixing by saying:

"Perusal of the literature has demonstrated that although several investigations have yielded information on a particular river under an existing flow condition the data necessary to predict and understand the diffusion phenomenon are not available. It is obvious that in order to more fully delineate the parameters involved in the overall mixing process in inland waterways, controlled data from field scale measurements are required."

Research Needs

Current research needs in this area are being attacked by Krenkel, who notes the following objectives of his project.

"The specific objectives of this investigation were as follows:

(1) To determine the applicability of the mathematical model describing turbulent diffusion with convection in open channel flow:

$$\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} - \bar{u} \frac{\partial C}{\partial x} \qquad (1)$$

in describing the concentration gradients for a point or line source of waste contaminant in two-dimensional flow.

(2) To determine the relation between equation (1) and the conventionally defined eddy diffusivity, D :

$$\frac{\partial C}{\partial t} = D_E \frac{\partial^2 C}{\partial x^2} \qquad (2)$$

in a homogeneous turbulent field.

(3) To examine the methods of determination of these mixing coefficients in the model and to determine the practicability of these methods for field scale studies.

(4) To evaluate diffusion and longitudinal mixing coefficients for artificial and natural channels in terms of conventionally used hydraulic parameters.

(5) To correlate turbulent diffusion characteristics of natural streams to the reaeration capacity and thereby the waste assimilative capacity.

(6) Utilizing pulse testing techniques, to develop the frequency response characteristics of various streams under differing hydraulic conditions.

(7) To test the model and techniques developed as a result of these model studies on the prototype, i. e., field scale studies in a natural river.

Although these objectives appear to be quite optimistic, a logical solution to the overall mixing process in inland waterways requires that each be subjected to analysis. Also the experimental procedures may be designed such that information pertinent to each phase of the investigation will be obtained."

The progress of his work is briefly summarized below.

"Because the initial phases of these investigations were largely involved with equipment design and refinement of methodology, the major portion of the experimental data will be obtained in the ensuing months. It is expected that sufficient data will be produced by October of 1964 such that the desired analyses can be performed, both in the laboratory flume and in the selected TVA rivers."

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OPERATIONS RESEARCH FOR WATER QUALITY MANAGEMENT

MATHEMATICAL ANALYSIS

Existing Information

The mathematical analysis and optimization of complex streamflow regulation systems is a relatively new field, but a vital one. Work in this area is being pioneered by Thomas and his co-workers at Harvard University and Kneese with Resources of the Future, Inc., among others. In their final report on "Operations Research in Water Quality Management," U. S. Public Health Service Project Number WP-00111, Thomas and Burden[133] have attempted to show how the ability of various engineering alternatives to accomplish a given objective can be represented in mathematical terms. These are called technological functions. Once this has been done for a given situation, they employ techniques for relating the effect of several engineering alternatives and then optimizing the entire system. The mathematics needed to accomplish this are, of course, complicated and sophisticated, and Thomas has had to develop new mathematical approaches to overcome gaps in the state of the operations research art, but progress has been made and is continuing in this area.

Further progress is essential since this is the only known method of optimizing the design of a complicated streamflow regulation project. Such a project might involve impoundments, rivers, water treatment and wastewater treatment plants, industries, hydro and thermal power plants, uncontrolled pollutional discharges, recreational areas, flood control projects, and transportation and irrigation systems in any number and combination. Each of these contains several design as well as operating variables, each of which in turn influences the downstream water quality at some given point. The complexity of even a small river basin such as the Lehigh Basin, which has been studied by Thomas[133] and his group, is enormous. Only through an operations research approach, however, can the best design and operation of such a river basin facility be accomplished.

All of the sophisticated scientific knowledge that may be amassed eventually to allow the understanding and prediction of impoundment and stream behavior will be of maximum benefit when this knowledge can be integrated into an optimum design for an overall river basin. One example of the current use of available systems analysis techniques, despite their shortcoming, is in a paper by Thomann,[134] "Use of Systems Analysis in Estuarine Water Pollution Control." Good agreement was obtained between predicted and actual dissolved oxygen concentrations at Torresdale, Pennsylvania.

Progress in this area is important from another point of view. A mathematical analysis of a design often gives insight into the most sensitive variable in the design. For example, in the design of a streamflow regulation project, changing each of the variables in the equations independently reveals which variable change causes the greatest change in the overall solution to the problem. Once the most sensitive variable has been determined, the most benefit is gained by emphasizing research effort related to this factor. Through this process the major research effort is placed on the most critical variable.

The growing interest in the field of the use of mathematical analysis for the solution of water quality problems was indicated by the attendance of 24 persons at a 1-day symposium, April 6, 1963, organized by Dr. Richard L. Woodward, formerly of the U. S. Public Health Service. This informal gathering followed the Symposium on Streamflow Regulation for Quality Control, April 3-5, 1963, sponsored by the U. S. Public Health Service in Cincinnati, Ohio. The purpose of this meeting was to bring the researchers in this area together to meet one another and to exchange views. At the lively all-day discussion the concensus was that this is a vital area in which vast amounts of additional work are needed.

Research Needs

The research needs in this area involve both mathematics and engineering. New mathematical techniques are needed to further refine existing capabilities. More-refined engineering data are needed to be used in the mathematical formulations. An example of the latter need may be found in chapter 3 of "Operations Research in Water Quality Management,"[133] which is titled "Queueing Model for Pollution Transport in Streams." This chapter is concerned with the development of mathematical techniques for the formulation of the complex process of pollution transport in streams. Some very sophisticated mathematics for accomplishing the above mentioned objective have been developed, but the present weak point in the method is the understanding of such items as: the mechanism for the degradation of organic wastes, the role of bottom deposits, and the role of photosynthetic oxygen production in the overall oxygen balance. Only further engineering research can strengthen these points.

As mentioned previously, the mathematician can often indicate the variable that requires the most research, that is, the one upon which the final result is the most dependent. The mathematician, however, must recognize that his current data may be insufficient for establishing the most sensitive variable in a water quality management problem. Information and research, therefore, must flow in both directions. Engineering research must provide improved information on scientific phenomena to the mathematician so that he can refine his mathematical analyses, and feed back to the researcher a better estimate of where additional work needs to be done. This continual exchange of information requires additional education of both groups, and is essential if systems analysis is to become a truly beneficial tool.

ECONOMIC ANALYSIS

Existing Information

Cost/Benefit Ratio. Most of the writings on this topic are concerned with the problem of evaluating the economic benefits provided through the regulation and management of some particular water resource, such as providing a certain volume of water in a particular location or preventing flood damage. The losses that occur through failure to meet a water quality or quantity objective, or as an associated effect of providing other benefits, are also involved. In the situation where additional storage capacity for water supply is provided in a multi-purpose impoundment, the economic benefits have, in the absence of any better method, traditionally been calculated as equal to the cost of providing an equivalent supply from the next most feasible source in the absence of the project. This may be a single-purpose impoundment, a well supply, or a supply purchased from some other system already in existence. In the case of storage provided for the purpose of regulating a stream for water quality control, benefits were formerly computed on the basis of the cost of removing a pound of BOD from the stream. For several reasons this concept has been abandoned, and the method now applied is the same as that used in evaluating municipal water supply benefits. The use of this method in this case, however, is even more questionable than in the case of water supply, but in the absence of anything better must be relied upon. Current research by economists and mathematicians has as its objective the development of a procedure that will yield a more realistic monetary evaluation of benefits attributable either to the provision of municipal and industrial water or to the maintenance of water quality.

Chapter 7, entitled "Imputed Benefits of Municipal Water Supply," of "Operations Research in Water Quality Management"[133] describes a method of assigning a value to municipal water supply and presents the mathematics necessary to handle a small example. This method is based on determining the increase in monetary benefits that would occur if the water supply requirement was reduced by one unit and this unit was diverted to an alternative use that has a calculable monetary benefit. For a given situation, an imputed benefit for the municipal water is thereby determined.

The book *The Value of Water in Alternate Uses*[135] takes a somewhat different approach. In the example cited, a given quantity of water is to be distributed between the San Juan and Rio Grande basins in New Mexico. The object of this analysis is to determine the most beneficial distribution and ultimate uses of this water. The possible uses are irrigation, municipal-industrial water supply, and recreation. Different volumes of water are assigned to each of these uses, and eight models are analyzed economically to determine which model would increase the gross product of the state the most. This analysis is made by calculating the increase in revenue that would come into the state for each particular combination. Through this technique the most beneficial division of this San Juan river water was determined.

In "The Animal Farm" Thomas[136] addresses himself to the problem of the determination of a mathematical model for the discussion of quality criteria for control of the environment. In this article he suggests that every quality criterion established contains an implied cost/benefit ratio and that the cost/benefit ratio should be taken into account when criteria are selected for the model.

Still another approach is contained in the report "Economic Evaluation of Water, Part III, An Interindustry Analysis of the California Water Economy" by Lofting and McGauhey.[137] This analysis is based, in general, on the Leontief analytical system, which is often known as the input-output method. This method involves constructing an input-output table in which output of each industry is distributed among other industries as their input for further processing. In this study, the average water use pattern for California industries is superimposed on an approximate interindustry transaction matrix for the same period. By this method water uses and requirements are correlated to the general flow of money and products through the large economic system. For example, a principal user of water is agriculture, and a number of industries make fairly heavy demands on agriculture for their product input; continual inputs of water to agriculture are therefore necessary to maintain the economic health of the dependent industries.

These four examples give some insight into the mathematical approaches being used to attempt to evaluate costs and benefits for water resource systems. The classic reference in this area is *Design of Water Resource Systems* by Maass, Hufschmidt, Dorfman, Thomas, Marglin, and Fair.[138] This book, popularly known as "The Harvard Blue Book," is the culmination of 5 years work by the personnel of the Harvard Water Program.

Recreation. Methods for calculating the economic benefits that realistically result from provision of facilities for outdoor recreation have been given some attention by economists. The rapidly increasing demand for water-oriented recreation, stemming from such factors as increases in population, leisure, incomes, mobility, and urbanization, prompted creation of the Outdoor Recreational Resources Commission by Public Law 85-470 in 1958 to determine the nation's needs in this area up to the year 2000. The economic gains from the provision of these facilities must be evaluated if the correct cost/benefit ratio for a water resources system containing recreational facilities is to be determined. Several methods are available for attempting this calculation, although each has its deficiencies.

In gathering information for "The Value of Water and Alternate Uses," Wollman[135] circulated questionaires to sportsmen and recreationists in an attempt to determine the amount of money that the users of a recreational facility spend. These costs include items such as the cost of gasoline to make the trip, the cost of equipment used at the site, and the cost of food consumed at the site. Similar expenditures per acre of recreational facility or mile of stream are then presumed to be applicable to new recreational facilities in the area. The size of a new facility would be a measure of the increased

flow of money generated by the new facility.

Clawson[139] in her paper "Methods of Measuring the Demand for and Value of Outdoor Recreation" uses a somewhat different approach. Her method makes use of a demand curve for a recreational area. The method relates the cost of a visit to number of visits (the lower the cost, the greater the visits) and uses this relationship to determine the economic worth of the recreational area. Revenues obtained from monies spent inside a park decline when entrance fees are charged because of decreasing visits. The relationship between entrance fees and number of visits permits determination of the optimum entrance fee for maximum income. The value of the resource is then taken as the capitalized net profit resulting from imposing the most profitable entrance fee. This is a useful approach, but has limitations because of simplifying assumptions. These are discussed by Knetsch[140] in his paper "Outdoor Recreation Demands and Benefits." This article takes into account other factors such as increased land values in close proximity to a recreational area and the effect of time of travel to a recreational area.

The perfect method of evaluating these real and often high monetary benefits from recreational areas has not yet been determined, but improvements are being made continually.

Loss Functions. Some economists are giving attention to determining loss functions. A loss function is an expression of the method of calculating an economic or monetary loss that occurs when some water criteria is not met, whether it be a quality or quantity criterion. In industrial terms, this might be an increased production cost because of the necessity of treating process water more intensively at certain times of the year because of a change in some particular quality characteristic. In municipal terms, an economic loss might occur if an insufficient quantity of water at a particular time of the year causes water restrictions in a given municipality, restricts new home construction, or influences industrial expansion. Determination of these loss functions is important. If streamflow regulation projects could prevent an economic loss and the loss could be calculated, this amount of avoided monetary loss could rightfully be credited as a benefit to the project. This is a logical extension of the methodology applied to flood control or highway evaluation.

Specific references on this subject were not found, but Bower at the University of New Mexico is determining loss functions for the particular industries in his area with respect to possible changes in water quality. Extensions of this work are necessary if the systems analysis approach is to be truly complete.

Research Needs

Research by economists, sociologists, and engineers in the area of economic analysis is needed to improve the economic evaluation of streamflow regulation projects. As was stated in the section on mathematical analysis, further scientific information is necessary to improve the data used in economic analyses. For example, in the important

area of the development of loss functions, engineering research designed to develop new treatment techniques that will insure the maintenance of a good quality finished water during periods of raw water quality deterioration is necessary. The construction and operating costs of plants that would use these new treatment techniques could then be integrated into the economist's loss functions, since the cost of this additional treatment would truly be an economic loss caused by failing to meet some raw water quality objective. In some cases the failure to meet a water quality objective can be overcome by: (1) application or refinement of existing treatment methods, (2) use of an additional source of supply, or (3) use of an entirely new treatment scheme. Whichever alternative is needed, the engineer must be able to supply the economist with the proper alternative, and this cannot be done without further research in the area of water and wastewater treatment. If the failure cannot be overcome, a loss in income will result because of lower production or the cost of a shift to another activity.

In the economic and social area, not only must improved methods of manipulating the monetary values involved in water resources systems be developed, but also additional attention must be given to the social aspects of the problem. Considerable effort on studies of the motivation and behavior of the general public in the important area of willingness to spend tax money on water quality control systems must be made. The finest water resource system design, carefully optimized by mathematicians, economists, and engineers, may well be stymied because of an uninformed, unprepared, or disinterested voting public. Because of the competition for the consumer dollar, realistic methods for motivating people to spend tax money for these water quality control systems should be further investigated. Some of these problems were discussed in "The Social and Economic Aspects of Water Resource Quality Control,"[141] but more effort is needed.

CURRENT STREAMFLOW REGULATION PROJECTS AND FUTURE ACTIVITIES

CURRENT PROJECTS

The amendments to Public Law 660, Public Law 87-88, was passed on July 20, 1961; review of what has been done in the intervening years to implement this law is pertinent to this report. The current state of affairs was effectively summarized by Eugene W. Weber,[142] Deputy Director of Civil Works for Policy, Office of the Chief of Engineers, Corps of Engineers, in his paper "Relation of Regulation for Quality Control to Activities of the Corps of Engineers," presented at the Symposium on Streamflow Regulation for Quality Control, April 3-5, 1963, sponsored by the Robert A. Taft Sanitary Engineering Center. Portions of this paper are quoted blow.

> "The enactment of Public Law 87-88 on 20 July 1961, less than 2 years ago, has made it possible to give full consideration in the planning and development of the Corps of Engineers' water resources program to provisions for regulation of streamflow for water quality control purposes on a par with all other project purposes. I will outline briefly the import of this new authority on three categories of projects in the Corps' program: i. e., completed projects; those authorized, but not yet completed or started; and those being studied for possible future authorization.
>
> **Completed Projects**
>
> "The Corps, in 1962, had in operation 214 reservoir projects containing 169 million acre-feet of storage capacity, primarily for flood control and power purposes with provisions for recreational use at most and with storage for water supply at some. Needs for flow regulation for water quality control were considered in planning many of these projects, but due to the absence of a positive policy for Federal participation in providing for such regulation, specific measures for quality control were included in relatively few projects, such as Fall River, Toronto and Kanopolis Reservoirs in Kansas; Berlin, and Mosquito Creek Reservoirs in Ohio; Youghiogheny River Reservoir, Pennsylvania, and Tygart Reservoir, West Virginia.
>
> "The importance of low flow augmentation has been amply demonstrated in these earlier projects. For

example, the operation of Fall River Reservoir, Kansas, in the very severe drought in the 1950's provided vitally needed water supply and dilution of wastes involving six downstream municipalities as well as prevented complete shutdown of three refineries and other industries. As another example, the Berlin project, Ohio, was constructed in the early 1940's at the request of the War Production Board primarily for low flow regulation in the Mahoning River Basin to maintain maximum power and steel production in this highly industrialized valley. In view of the continued critical situation with respect to steel production, the method of operation specifically adopted as a war-time measure was continued until 1949 at which time a more balanced method of operation between flood control and low flow augmentation was adopted. Some of our very early studies of low flow augmentation in cooperation with the Public Health Service which were carried out as far back as the late 1930's established the need for the inclusion of regulatory storage in projects only recently undertaken, such as in Allegheny Reservoir above Pittsburgh. During this same early period, the Ohio River Pollution Survey was completed through our joint efforts. This provided a very valuable background not only in the planning of Corps projects, but to all other interests concerned with pollution of the Ohio River.

"Although water quality control was authorized as a specific purpose of only a few of our 214 completed reservoirs, some planned regulation for quality control is being made part of reservoir operating plans whenever it is consistent with the purposes for which the projects were authorized. Furthermore, in nearly all cases, the effect of regulation for authorized purposes is incidentally beneficial to water quality. Also, as we learn more about the effects of reservoir operations, steps can usually be taken to prevent adverse effects on water quality.

"On these completed projects two general courses of action are now possible. First, adjustments consistent with the authorized purposes of the projects, particularly in operations, can continue to be made in the light of experience and changing reguirements for water quality. Second, completed projects can be restudied, particularly in conjunction with basin-wide studies for additional projects to meet future needs and, when feasible, recommendations made to Congress for modification of existing projects in the interests of quality control. We do not have authority to modify completed projects to include quality control without further action by Congress.

Authorized Projects, Under Construction or Not Started

"Including those most recently authorized last year in Public Law 87-874, the Corps has authority to construct over 200 additional projects containing some 90 million acre-feet of storage. Of these 81 reservoirs with 56 million acre-feet of capacity have been placed under construction. On all of the projects not yet started and on those where planning for certain phases of construction is still under way, the new Public Law 87-88 provides a basis for considering modifications to previously authorized plans to include provisions for flow regulation for water quality control if the following criteria are met:

a. The modification of the project must be economically justified.

b. The status of the planning and construction of the project must be such that it is practicable to accomplish the necessary changes without undue delay or unreasonable increase in cost over that which would have been incurred if water quality control had been originally authorized as a project purpose.

c. The modification must not have material adverse effect on the purpose for which the project was authorized originally.

d. Satisfactory advice must be received from the Secretary, Department of Health, Education, and Welfare relative to the need for and the value of the water quality control storage.

e. The Congress must be informed of our intention to modify the project and of the views of the Secretary, Department of Health, Education, and Welfare, by letters to the Public Works and Appropriations Committees of the Senate and House.

"Last year we informed Congress that we were modifying two projects, John W. Flannagan Reservoir, Ohio River Basin, Virginia, and DeGray Reservoir, Ouachita River Basin, Arkansas, to include water quality control storage as a primary project purpose. We feel certain that many other authorized projects can be modified to include this important purpose as detailed planning studies proceed."

Later in his paper Mr. Weber further stated:

"First, through training of current employees and in new hiring, we are equipping our own organization with personnel who encompass the wide range of disciplines needed to work out solutions to water problems. These included engineers with various specialties including some who will try to solve water quality problems, and

biologists, economists, lawyers and others who are needed to assimilate the complex considerations involved in modern water resource development plans.

"Secondly, we are trying to work out appropriate and effective arrangements for coordination and distribution of effort among all agencies who can and should contribute to solution of water problems. Insofar as water quality considerations are concerned, we are looking to the Department of Health, Education, and Welfare for both day-to-day advice, and continuing, concurrent consideration of long-range studies."

As mentioned in Public Law 660 as amended, consideration must be given to inclusion of storage for regulation of streamflow for the purposes of water quality control in impoundments constructed by the Bureau of Reclamation. In his talk, "Relation of Regulation for Quality Control to Activities of the Bureau of Reclamation," given at the Symposium on Streamflow Regulation for Quality Control, April 3-5, 1963, sponsored by the Robert A. Taft Sanitary Engineering Center, Mr. D. R. Burnett, Chief, Division of Project Development, Bureau of Reclamation, discussed this point. By provision of various Acts, the Bureau of Reclamation is authorized to investigate, construct, and operate projects to provide water for irrigation and multiple purposes in the 17 contiguous Western States.

Two quotations summarized the position of the Bureau on this topic. Mr. Burnett noted:

"There are numerous specific project authorizations for construction and operation of Reclamation projects, some of which include works specifically for water quality control. . . . In carrying out our work in the field of water quality, our experiences working with the Fish and Wildlife Service, the Public Health Service, and the National Park Service have been of paramount benefit. These agencies have the contacts and sources of information that are not readily available to the Bureau. They also have the knowledge in the biological field that is outside the normal experience of our Reclamation personnel. The use of these sources by our planners has allowed us to progress in water quality control work at an accelerated pace."

Other examples of current use of streamflow regulation for quality control are given in the following cases. In the Federal license to the Virginia Electric and Power Company, contained in the paper by Ragone and Peters,[10] is a requirement that states:

"In the event of temporary emergency conditions arising in performance of Requirements A and B, the Licensee will cooperate in good faith with the North Carolina State Department of Conservation and Develop-

ment, North Carolina State Stream Sanitation Committee and/or North Carolina Wildlife Resources Commission to take such reasonable steps in regards to the reductions permitted by item (1) under Requirement B as may be proper to meet the emergency conditions and in the interest of maintaining during such emergency conditions water quality in keeping with the standards required of class "C" waters by order of the North Carolina Stream Sanitation Committee effective September 1, 1957."

This emergency provision was put into operation in 1962 when a fish kill due to presence of industrial wastes and low dissolved oxygen concentration conditions took place in the Roanoke River. During this time extra water was released from the Virginia Electric and Power Company Reservoirs for quality control.

Another example of streamflow regulation for quality control was in the Ohio River in the fall of 1963. Although the Corps of Engineers' reservoirs in the affected area did not specifically have additional capacity for quality control water, at the height of the drought the Corps happened to be lowering the level of their reservoirs from summer pool to winter pool elevation. During this time, they calculated they were supplying one-half of the flow in the Ohio River with these releases. Fortunately, the severe portion of the drought ended just as the level of the Corps of Engineers reservoirs reached the winter pool elevation. Although there were some quality problems in the Ohio River at this time and a small fish kill, the situation probably would have been much worse had the Corps not been able to supply their water. Although this example of streamflow regulation for quality control was more of a lucky happenstance than a preplanned operation, it does show the potential advantages of streamflow regulation for quality control.

The preceding paragraphs indicate that, although all of the research needed in this area has not been done, projects designed to control water quality through streamflow regulation are a reality. Past research on the behavior of impounded water, together with accumulating experience in the operation of these projects, has brought us closer to an understanding of impoundments, thereby improving estimates of effects on water quality parameters and improving designs of projects. But, as this report has tried to indicate, in spite of the enormous literature on this subject, additional research work needs to be done.

FUTURE ACTIVITIES

In order to understand the behavior of impoundments and their influences on downstream water quality, additional research work is required. This work involves integrating existing information and filling in gaps, measuring effects in impoundments and streams that have been measured in other circumstances, and relating the environ-

ment to the measured effects. In some cases whole new areas of interest must be researched.

To begin to fill these needs, the Engineering Section at the Robert A. Taft Sanitary Engineering Center has started several laboratory, field, and desk-top studies on various phases of the overall problem. In each case the project began with an extensive literature review, for only through the integration of knowledge from a wide range of disciplines augmented by research can answers to the very complicated interrelated problems associated with impoundment behavior be forthcoming. The current (1964) state of the Engineering Section's research is summarized in an article by Symons, Weibel, and Robeck,[144] in "Impoundment Influences on Water Quality," published in the *Journal of the American Water Works Association.*

Even when impoundment behavior is understood, other problems will still be associated with streamflow regulation projects. One question is: What criteria should be used to measure a good quality water? In the past, heavy emphasis has been placed upon dissolved oxygen concentrations, although even here the desirable level is subject to debate. Other quality characteristics must also be used to judge water, however. A second question concerns the monetary benefits associated with meeting these criteria. These must become available, as must the losses associated with temporary violation of one of these criteria. Currently, projects are often designed on a cost-minimization basis rather than on a benefit-maximization basis, because benefits are not truly calculable.

A third question involves the legal problems associated with streamflow regulation. Examples are the water rights problems and the problems caused by groups such as the recreationists who prevent water level changes that would interfere with their activities.

Finally, attention must be given to the methods other than streamflow regulation for the solution of water pollution problems. For example, if the construction and operating costs for water treatment plants were accurately known, the additional costs of treatment for the removal of a given pollutant could be compared with the cost of providing dilution water. Another possibility would be the use of one or more techniques being developed by the Advanced Waste Treatment Research group at the Robert A. Taft Sanitary Engineering Center. In some instances, protection of water quality might be less expensive if advanced techniques were used, rather than streamflow regulation. A third example would be the possibility of aerating a stream mechanically, instead of supplying oxygen to a critical zone with impoundment releases. One million gallons of water with a dissolved-oxygen concentration of 8 milligrams per liter contains only 66.5 pounds of oxygen; therefore, stream aeration may be less expensive than impoundment releases for providing oxygen. References 145 and 146 describe one of many such devices for aeration. Storage of wastes with controlled discharge is another useful technique for the

protection of the oxygen resources of a stream. These alternatives are important and realistic, since streamflow regulation alone will not solve a basin-wide pollution problem. An example of the basin-wide approach to pollution abatement, which integrates numerous pollution control methods, is in the Ruhr Basin in Germany. This was discussed by Kneese[147] in an article, "The Ruhr's Unique Approach to Water Management."

Although these other problems exist, current research attention is focused on the impoundment itself. The research goals of this portion of the overall project are, in general, designed to measure the influences of impounding water on water quality, to relate these influences to the environment so that they may be projected to other environments, and to predict the influence of releases on the downstream water. Attainment of these goals will allow the prediction of the behavior and influence of new impoundments so that alternate sites, alternate methods of operation, or alternate treatment plans may be accurately integrated into a mathematical chemical and economic basin-wide analysis. Only through optimizing basin designs, using improved mathematical and economic techniques with better water quality behavior input data, and realistic alternative proposals can streamflow regulation projects for water quality control be considered truly successful. The information supplied by the research suggested in the body of this report should allow this hope to become a reality.

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GPO 823-506-7